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TREATABILITY STUDY IN SUPPORT OF MONITORED NATURAL ATTENUATION AT SITE S-1, ZONE 5, KELLY AIR FORCE BASE TX

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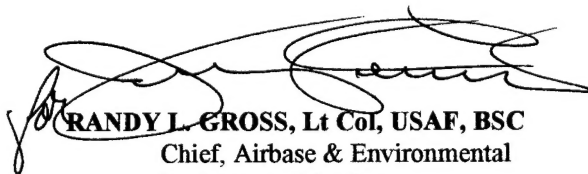THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.

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This report presents the results of a treatability study (TS) to evaluate the potential effectiveness of monitored natural attenuation (MNA) as a remedial option for groundwater contaminated with chlorinated benzene compounds at Site S-1, located at Kelly Air Force Base (AFB), Texas. Although other contaminants were found at Site S-1 at relatively low concentrations, this TS will focus on the chlorinated benzene compounds present in the groundwater plume. Hydrogeologic and groundwater chemical data collected for this report can be used to evaluate the effectiveness of various engineered remedial options; however, the results of this TS will be used in support of MNA with long-term monitoring (LTM) for restoration of groundwater contaminated with chlorinated benzene compounds. The work performed as part of the TS is not intended to fulfill the requirements of a contamination assessment report, a remedial action plan (RAP), or any other document specified in federal or state regulations; rather, it is provided for the use by the Base, its prime environmental contractors, and regulators to present information on the viability of the MNA alternative for chlorobenzene residuals at Site S-1.

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EXECUTIVE SUMMARY

This report presents the results of a treatability study (TS) performed by Parsons Engineering Science, Inc. (Parsons ES) at Site S-1, Zone 5 at Kelly Air Force Base (AFB), Texas to evaluate natural attenuation of dissolved chlorinated benzenes in groundwater. The TS focused on the fate and transport of dissolved chlorinated benzenes, which are present at high concentrations at the site. Other contaminants detected at the site (fuel hydrocarbons and chlorinated ethenes) were present at lower concentrations, and the evaluation of their significance was limited to their influence on the natural attenuation of chlorinated benzenes. The site history and the results of the soil and groundwater investigations conducted previous to this TS also are summarized and evaluated in this report.

Organic contaminants detected in groundwater for this TS included fuel hydrocarbons, chlorinated ethenes, and chlorinated benzene compounds. This TS confirmed that chlorobenzene (CB) in groundwater is the most extensive contaminant plume at Site S-1. Other chlorinated benzene compounds present at Site S-1 included 1,2,4-trichlorobenzene (TCB) and all three dichlorobenzene (DCB) isomers. Chlorinated ethene contamination also was detected, but appears to be emanating primarily from a source outside of Site S-1.

Contaminant, electron acceptor, and biodegradation byproduct isopleth data for Site S-1 provide strong evidence of the biodegradation of dissolved contaminants. Concentrations of dissolved oxygen (DO) in the CB plume have been depleted, indicating that substantial aerobic biodegradation of contaminants has occurred (and continues to occur) at Site S-1. Microcosm study results indicate the presence of a viable population of CB-degrading microorganisms whose rate of CB metabolism is limited only by the rate of oxygen supply to the aquifer. Significant CB degradation appears to occur in the source area at Site S-1; however, high CB concentrations continue to migrate up to 2,000 feet from the source area under anaerobic conditions. Field-scale, first-order CB decay rates computed using data from Site S-1 range from 7.9×10^{-4} day^{-1} to 1.9×10^{-2} day^{-1}.

Groundwater data indicate that TCB, DCB, trichloroethene (TCE), and dichloroethene (DCE) are being reductively dechlorinated at the site through the microbial use of natural organic carbon and groundwater contaminants as substrates. Groundwater is highly reduced in the source area and contaminants known to be susceptible to reductive dechlorination processes generally are being degraded prior to migration off base.

The numerical groundwater flow and contaminant fate and transport model Bioplume III was used to predict CB migration under the effects of natural attenuation and engineered source reduction activities proposed as part of prior feasibility studies. A source reduction scenario was modeled that considered the effects of source excavation and subsequent SVE on the longevity of the groundwater plume. The simulation assumed that source light non aqueous phase liquid (LNAPL) would be reduced by at least 90 percent during a 4-year treatment period beginning in 1999, followed by natural weathering of remaining source LNAPL at a geometric rate of 3 percent per year. Model predictions indicate that the effects of natural attenuation currently stabilize the CB

plume, and future weathering and remediation of the source area will enhance the rate of plume diminishment. CB concentrations exceed the Texas Risk Reduction Standard 2 value of 100 μg/L at a single well closest to the base and CB concentrations at this well are predicted to attenuate below 100 μg/L by calendar year 2035. If source remediation is performed.

To verify model predictions, and to ensure that the selected technologies are meeting objectives, periodic sampling of nine long-term monitoring (LTM) wells and three point of compliance (POC) wells to monitor the long-term migration and degradation of the dissolved CB plume is recommended. If data collected under the LTM program indicate that the selected remedial alternative is not sufficient to reduce CB concentrations at downgradient LTM and POC well locations to levels considered protective of human health and the environment, additional corrective actions may be required to remediate groundwater at the site. Alternately, if results show dramatic reductions or continued stabilization of the contaminant plume, the frequency of LTM could be reduced or terminated.

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LIST OF FIGURES (Continued)

ACRONYMS AND ABBREVIATIONS

μg	micrograms
μg/kg	micrograms per kilogram
μg/L	micrograms per liter
μL	microliters
°C	degrees centigrade
°F	degrees Fahrenheit
ΔG_r^0	Gibbs free energy of the reaction
μ	microns
2-D	two-dimensional
AFB	Air Force Base
AFCEE	Air Force Center for Environmental Excellence
AFMC	Air Force Material Command
AFRL/MLQE	Air Force Research Laboratory, Materials and
bgs	below ground surface
BTEX	benzene, toluene, ethylbenzene, xylenes
$CaCO_3$	calcium carbonate
CAH	chlorinated aliphatic hydrocarbon
CB	chlorobenzene
cm	centimeter
cm/sec	centimeters per second
CMS	corrective measure study
cm^3	cubic centimeter
DCB	dichlorobenzene
DCE	dichloroethene
DNAPL	dense nonaqueous-phase liquid
DO	dissolved oxygen
DOC	dissolved organic carbon
DOD	Department of Defense
EMRO	Environmental Management Restoration Organization
EP	extraction procedure
ES	Engineering-Science, Inc.
FFS	focused feasibility study
FS	feasibility study
ft/day	feet per day
ft/ft	foot per foot
ft/min	feet per minute
ft/sec	feet per second
ft^2/day	square feet per day
gpm	gallons per minute
H+	hydrogen ion
HDPE	high density polyethylene
HNUS	Halliburton NUS

HPLC	high performance liquid chromatograph
ID	inside diameter
IM	interim measure
IMS	interim measure system
IRP	Installation Restoration Program
IWTP	industrial wastewater treatment plant
kg/L	kilograms per liter
k_{oc}	soil sorption coefficient
L/min	liters per minute
LCS	laboratory control sample
LLNL	Lawrence Livermore National Laboratories
LMB	laboratory method blank
LNAPL	light non-aqueous phase liquid
LTM	long-term monitoring
MCL	maximum concentration limit
mg/kg	milligrams per kilogram
mg/L	milligrams per liter
mg/ml	milligrams per milliliter
ml	milliliter
MNA	monitored natural attenuation
MOC	method of characterization
msl	mean sea level
mV	millivolt
N	nitrogen
NAPL	non-aqueous phase liquid
NAPL	non-aqueous phase liquid
ND	not detected
nm	nanometers
OD	outside diameter
ORD	Office of Research and Development
ORP	oxidation-reduction potential
OSWER	Office of Solid Waste and Emergency Response
Parsons ES	Parsons Engineering Science, Inc.
PCA	tetrachloroethane
PCB	polychlorinated biphenyl
PCE	tetrachloroethene
PID	photoionization detector
POC	point of compliance
POL	petroleum, oils, and lubricants
PRG	preliminary remediation goal
PVC	polyvinyl chloride
QA/QC	quality assurance/quality control
RAP	remedial action plan
redox	reduction/oxidation

RFH	radio frequency heating
RI	Remedial Investigation
RMS	root mean squared
RNA	remediation by natural attenuation
SA-ALC	San Antonio Air Logistics Center
SAIC	Science Applications International Corporation
SDWA	Safe Drinking Water Act
SVE	soil-vapor extraction
SVOCs	semivolatile organic compounds
TCA	trichloroethane
TCB	trichlorobenzene
TCE	trichloroethene
TCLP	toxicity characteristic leaching procedure
TD	total depth
TDS	total dissolved solids
TeCB	tetrachlorobenzene
TMB	trimethylbenzene
TNRCC	Texas Natural Resource Conservation Commission
TOC	total organic carbon
TPH	total petroleum hydrocarbons
TS	treatability study
USAF	United States Air Force
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VC	vinyl chloride
VOC	volatile organic compound

SECTON 1

INTRODUCTION

This report presents the results of a treatability study (TS) to evaluate the potential effectiveness of monitored natural attenuation (MNA) as a remedial option for groundwater contaminated with chlorinated benzene compounds at Site S-1, located at Kelly Air Force Base (AFB), Texas. Although other contaminants were found at Site S-1 at relatively low concentrations, this TS will focus on the chlorinated benzene compounds present in the groundwater plume. Hydrogeologic and groundwater chemical data collected for this report can be used to evaluate the effectiveness of various engineered remedial options; however, the results of this TS will be used in support of MNA with long-term monitoring (LTM) for restoration of groundwater contaminated with chlorinated benzene compounds. The work performed as part of the TS is not intended to fulfill the requirements of a contamination assessment report, a remedial action plan (RAP), or any other document specified in federal or state regulations; rather, it is provided for the use of the Base, its prime environmental contractors, and regulators to present information on the viability of the MNA alternative for chlorobenzene residuals at Site S-1.

1.1 PURPOSE AND BASIS

Parsons Engineering Science, Inc. (Parsons ES) was retained by the United States Air Force Research Laboratory (AFRL) Technology Transfer Division under contract F11623-94-D-0024 to conduct site characterization and groundwater modeling to evaluate the scientific defensibility of MNA with LTM as a remedial option for groundwater contaminated with chlorinated benzenes at Site S-1. The overall objective of this report are two-fold and include: 1) to provide the base, regulators, and contractors the information necessary to make informed decisions as to the benefits or disadvantages of natural attenuation at Site S-1; and 2) to contribute information in support of the CB natural attenuation initiative being conducted by AFRL. AFRL desires to effectively disseminate the information in this report for use in the Corrective Measure Study (CMS) and feasibility study (FS) currently being prepared for the site and evaluated by the Base, the Texas Natural Resource Conservation Commission (TNRCC), and other agencies responsible for establishing and approving site closure plans at Kelly AFB.

As used in this document, natural attenuation refers to the stabilization or destruction of *in-situ* contaminants by physical, chemical, or biological means, whereas MNA refers to the overall administered use of natural attenuation through LTM and institutional or land use controls. The US Environmental Protection Agency (USEPA) recognizes that MNA is an alternative means of achieving remediation objectives at sites appropriate for its use. The term monitored natural attenuation as per USEPA Office of Solid Waste and Emergency Response (OSWER) Directive 9200.4-17 (USEPA, 1997) refers to:

> *"...reliance on natural attenuation processes (within the context of a carefully controlled and monitored site cleanup approach) to achieve site-specific remedial objectives within a time frame that is reasonable compared to that offered by other more active methods. The natural attenuation processes that are at work include a variety of physical, chemical, or biological processes, that, under favorable conditions, act without human intervention to reduce the mass, toxicity, mobility, volume, or concentration of contaminants in soil or groundwater. The in-situ processes include biodegradation; dispersion; dilution; sorption; volatilization; and chemical or biological stabilization, transformation, or destruction or contaminants."*

Although USEPA acknowledges the technology advancements made in the science of natural attenuation over recent years, it recognizes that natural attenuation should be used with engineering and institutional controls commensurate with the uncertainty associated with site conditions. Therefore, performance monitoring and source control are essential components to be considered in a natural attenuation remedy and as part of this TS report. Specifically, the results presented herein can be used to justify the future role of MNA with LTM in site remediation, either as the sole remediation alternative or in conjunction with engineered remedial alternatives proposed in current FFSs prepared for the site. The most recent FFS addressing groundwater at Site S-1 (CH2M Hill, 1998) recommends source excavation and offsite disposal in combination with soil vapor extraction (SVE) (upgradable to a dual-phase extraction system) to address both mobile- and residual-phase soil contaminants at the site. The effects of these actions on MNA, the use of MNA in combination with limited groundwater pump-and-treat, and the effects of MNA without source removal are considered in this TS report.

MNA has many advantages that should be considered in the selection of remedial activities (Wiedemeier *et al.*, 1998):

- Contaminants can be transformed to innocuous byproducts (e.g., carbon dioxide or water), not just transferred to another phase or location within the environment;

- Current pump-and-treat technologies are energy-intensive and generally not effective in reducing residual contamination (particularly with the presence of light nonaqueous phase liquid (LNAPL) or dense nonaqueous phase liquid (DNAPL);

- The process is nonintrusive and allows continuing use of facilities during remediation;

- Engineered remedial technologies may pose a greater risk to potential receptors than MNA (e.g., contaminants may be transferred into another medium during remediation activities); and

- MNA is often less costly than conventional, engineered remedial technologies.

A potential disadvantage of MNA is that, in some cases, natural attenuation rates are too slow to make MNA a practical remedial alternative, and some biodegradation intermediates are more toxic than the parent compound. In addition, natural attenuation is subject to potential future contaminant releases and to natural changes in local

hydrogeologic conditions, including changes in groundwater gradients/velocity, pH, electron acceptor concentrations, or electron donor concentrations.

1.2 REPORT OBJECTIVES FOR DOCUMENTING MONITORED NATURAL ATTENUATION

Data derived from field investigation activities performed as part of this study and from other available reports were used in this report to satisfy several project objectives that were previously described in the Site S-1 MNA work plan (Parsons ES, 1998). The technical objectives necessary to support natural attenuation at Site S-1 are resummarized in Table 1.1.

This TS contains nine sections, including this introduction, and five appendices. Section 2 summarizes site characterization activities. Section 3 summarizes the physical characteristics of the study area. Section 4 describes the nature and extent of soil and groundwater contamination, and the geochemistry of soil and groundwater at the site. Section 5 describes the design of the conceptual hydrogeologic model and numerical groundwater flow and contaminant fate and transport model for the site; lists model assumptions and input parameters; describes sensitivity analyses, and calibration results of the modeling. Section 6 presents an analysis of the predicted effectiveness of MNA with proposed remedial actions at the site through evaluation of model output and presents a proposed LTM plan for the site. Section 7 presents the conclusions of this work and provides recommendations for further work at the site. Section 8 lists the references used to develop this document. Appendix A contains borehole logs, monitoring well construction diagrams, monitoring well development and sampling forms, previous aquifer test results, survey data, and selected historic soil and groundwater data used in this report. Appendix B presents groundwater sampling forms. Appendix B also contains soil and groundwater data collected as part of this TS on computer diskette. Appendix C contains model input parameters, calculations related to model calibration, and other materials used in groundwater modeling. Appendix D contains model input files. Appendix E contains cost calculations pertinent to the Section 6 MNA evaluation. Appendix E presents additional groundwater model simulations.

1.3 INSTALLATION DESCRIPTION AND HISTORY

Kelly AFB is located in Bexar County in south-central Texas, seven miles southwest of the center of San Antonio (Figure 1.1). The Base is bounded on the west by Lackland AFB, on the south by Military Highway and Leon Creek, on the east by the Missouri-Pacific Railroad yards, and on the north by Highway 90. The Base comprises an area of 3,929 acres [Halliburton NUS (HNUS), 1991]. Site S-1 is located within a few hundred feet of the northern Base boundary and west of two aboveground petroleum, oils, and lubricants (POL) tanks (Figure 1.2).

Kelly AFB was founded in 1917 as the first military air base in Texas. The Base has been involved in logistics and aircraft maintenance since 1957. The primary mission of

TABLE 1.1

REPORT OBJECTIVES

SITE S-1 MNA TS

KELLY AIR FORCE BASE, TEXAS

OBJECTIVE	ACTION ITEM AND SECTION
Objective 1: Estimate the effect of aerobic biodegradation in reducing chlorobenzene (CB) contamination at Site S-1.	• Review historical trends of CB concentrations in each well and along the centerline of the plume (Section 4); • Use collected data to define the extent of the CB plume and use dissolved oxygen concentrations to define aerobic locations in the aquifer (Section 4); • Estimate previous, current, and future field aerobic degradation rates of CB compounds using simple analytical models (Section 4); • Summarize the results of aerobic microcosm studies created from uncontaminated, previously contaminated, and currently contaminated aquifer sediments to determine if microorganisms exist that are capable of biodegrading chlorobenzene, to estimate their acclimation period, and to estimate laboratory CB degradation rates (Section 4).
Objective 2: Estimate the effect of anaerobic biodegradation in reducing trichlorobenzenes (TCBs), dichlorobenzenes (DCBs), and CB contamination at Site S-1.	• Review historic trends of TCBs, DCBs, and CB in each well and along the centerline of the plume to support natural attenuation results (Section 4); • Highlight geochemical trends in dissolved oxygen, nitrate, ferrous iron, sulfate, methane, and carbon dioxide concentrations to establish anaerobic zones in the aquifer and to document site conditions amenable to anaerobic degradation (Section 4); • Estimate field anaerobic degradation rates of TCB, DCB, and CB using simple analytical models (Section 4); • Summarize the results of anaerobic microcosm studies using collected soil and groundwater media from contaminated anaerobic locations. Determine if groundwater conditions are reducing enough to cause reductive dechlorination of TCB, DCB, and CB or direct oxidation of CB for comparison with field rate estimates (Section 4).

TABLE 1.1 (Concluded)

REPORT OBJECTIVES

SITE S-1 MNA TS

KELLY AIR FORCE BASE, TEXAS

OBJECTIVE	ACTION ITEM AND SECTION
Objective 3: Estimate the effectiveness of biodegradation in combination with other natural attenuation mechanisms at reducing current and future concentrations of TCB, DCB, and CB at Site S-1;	• Show measured groundwater elevations at Site S-1 to illustrate plume migration direction and groundwater flow gradients (Section 3); • Summarize soil total organic carbon (TOC) data collected at the site to be used for estimating contaminant sorption and contaminant migration velocities (Section 4); • Use estimated laboratory and field aerobic and anaerobic biodegradation rates and other attenuation mechanism estimates to model historical and future reductions of chlorinated benzene compounds within and downgradient from the source area at Site S-1 (Section 5).
Objective 4: Estimate the effectiveness of natural attenuation in combination with engineered treatment technologies at reducing current and future concentrations of TCB, DCB, and CB at Site S-1;	• Review recovery rates of the groundwater pump-and-treat system and its effect on groundwater flow characteristics and natural attenuation mechanisms at Site S-1 (Section 6); • Use existing and new soil data to better determine the vertical and horizontal distribution of non-aqueous phase liquid (NAPL) and the potential for effective source reduction by source excavation and SVE (Section 6); • Use soil and groundwater data and estimated biodegradation rates in a numeric fate and transport model designed to make future predictions of plume longevity under various site conditions (Section 6); and • Establish the effect of previous natural attenuation trends on the behavior of CB in the contaminant plume at the site.

TABLE 1.doc

New Mexico

Oklahoma

Arkansas

Louisiana

Texas

San Antonio

Houston

Kelly
Air Force Base

N

Not To Scale

FIGURE 1.1

LOCATION OF
KELLY AFB

Site S-1 MNA TS
Kelly Air Force Base, TX

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Denver, Colorado

Coreldraw1732351_nap 798 (no2 - cdr62)

IRP SITE S-1

KELLY AIR FORCE BASE

EAST KELLY

CROWSON DRIVE
MILITARY RESERVE BOUNDARY
BILLY MITCHELL ROAD
BILLY MITCHELL DRIVE
GEN MCMULLEN DR
CUPPLES ROAD
UNION PACIFIC R/R
GEN MITCHELL RD
BOXER DRIVE
VICKERS ROAD
MILITARY DRIVE WEST
DUGHTARA ROAD
STAMM AVENUE
UNION PACIFIC R/R
MILITARY RESERVE BOUNDARY
MILITARY RESERVE BOUNDARY

—N—

GRAPHIC SCALE IN FEET

0   2000   4000   8000

FIGURE 1.2

LOCATION OF SITE S-1

Site S-1 MNA TS
Kelly Air Force Base, Texas

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Denver, Colorado

Kelly AFB has been to support the San Antonio Air Logistics Center (SA-ALC) of the Air Force Logistics Command. The SA-ALC is the system support manager for the Military Airlift Command's C-5 Galaxy Jet Transport Fleet. The SA-ALC also manages more than half of the entire Air Force engine inventory and the fuels, oil, and petroleum program for the Air Force, including liquid oxygen, nitrogen, and special fuels. The Base is also host to approximately 56 tenant organizations representing the US Air Force, the US Army, the Department of Defense (DOD), and various other government agencies (HNUS, 1991). Under the Base Realignment and Closure Act, the SA-ALC at Kelly AFB is preparing for closure which must occur no later than the end of fiscal year 2001 (CH2M Hill, 1998). Several tenant organizations and select properties will be transferred to nearby Lackland AFB, and a large portion of the land now occupied by the Base will be redeveloped.

Site S-1 was used as an intermediate storage area for wastes to be reclaimed off-base (Figure 1.3). Wastes were stored at Site S-1 from the 1960s until 1973 (HNUS, 1991). Wastes, including mixed solvents, carbon cleaning compounds, and waste POLs, were stored in aboveground tanks that were located at the bottom of an open pit, or sump area. Contaminant releases during the former transport and storage of wastes at Site S-1 resulted in soil and groundwater contamination. The western two-thirds of Site S-1 was used for temporary storage of electrical transformers and scrap metal over an unconfirmed period (Radian, 1984).

Currently, the western half of the site is a large, grass-covered field and the eastern half of the site is fenced and covered by gravel. Off-base land use near Site S-1 area is mixed residential and commercial in the residential neighborhood north/northeast of the site (beyond the perimeter fence located a minimum distance of 100 feet north of the former sump area) and light industrial on-Base (HNUS, 1996).

1.4 DATA REVIEW

The following sections are based upon review of data from the following sources:

- IRP Phase I, Records Search (Engineering-Science, Inc.[ES], 1982) -- Various sites at Kelly AFB were identified as potentially contaminated based on past disposal practices. Site S-1 was identified as a site containing solvents.

- IRP Phase II, Stage 1, Field Evaluation (Radian, 1984) -- The purpose of this evaluation was to determine whether contamination had resulted from past waste disposal practices or from fuel or other spills. Drilling activities that began in November 1983, monitoring wells QQ, RR, and VV were installed. In December 1983, groundwater samples were collected from the wells for laboratory analysis. Results indicated shallow groundwater contamination.

- IRP Phase II, Stage 2, Confirmation/Quantification (Radian, 1988) – Monitoring wells S101 through S104 were installed. Groundwater samples were collected from the seven existing wells for laboratory analysis. Results showed that CB and benzene were present at the greatest concentrations. One soil sample (auger cuttings from S104) was collected for extraction-procedure (EP) toxicity and ignitability; results indicated that the sample was non-hazardous.

GROWDON DR

APPROXIMATE LIMIT
OF FORMER SUMP
AREA

APPROXIMATE LIMIT
OF FORMER
TOPOGRAPHIC
DEPRESSION AREA

GROUNDWATER COLLECTION
AND CONVEYANCE LINES

P1593

P1594

P1592

Existing S-1
Treatment System

W THOMPSON RD

P1573

P1573

P1594

LEGEND

—x——x— FENCE

N

0   75   150
FEET
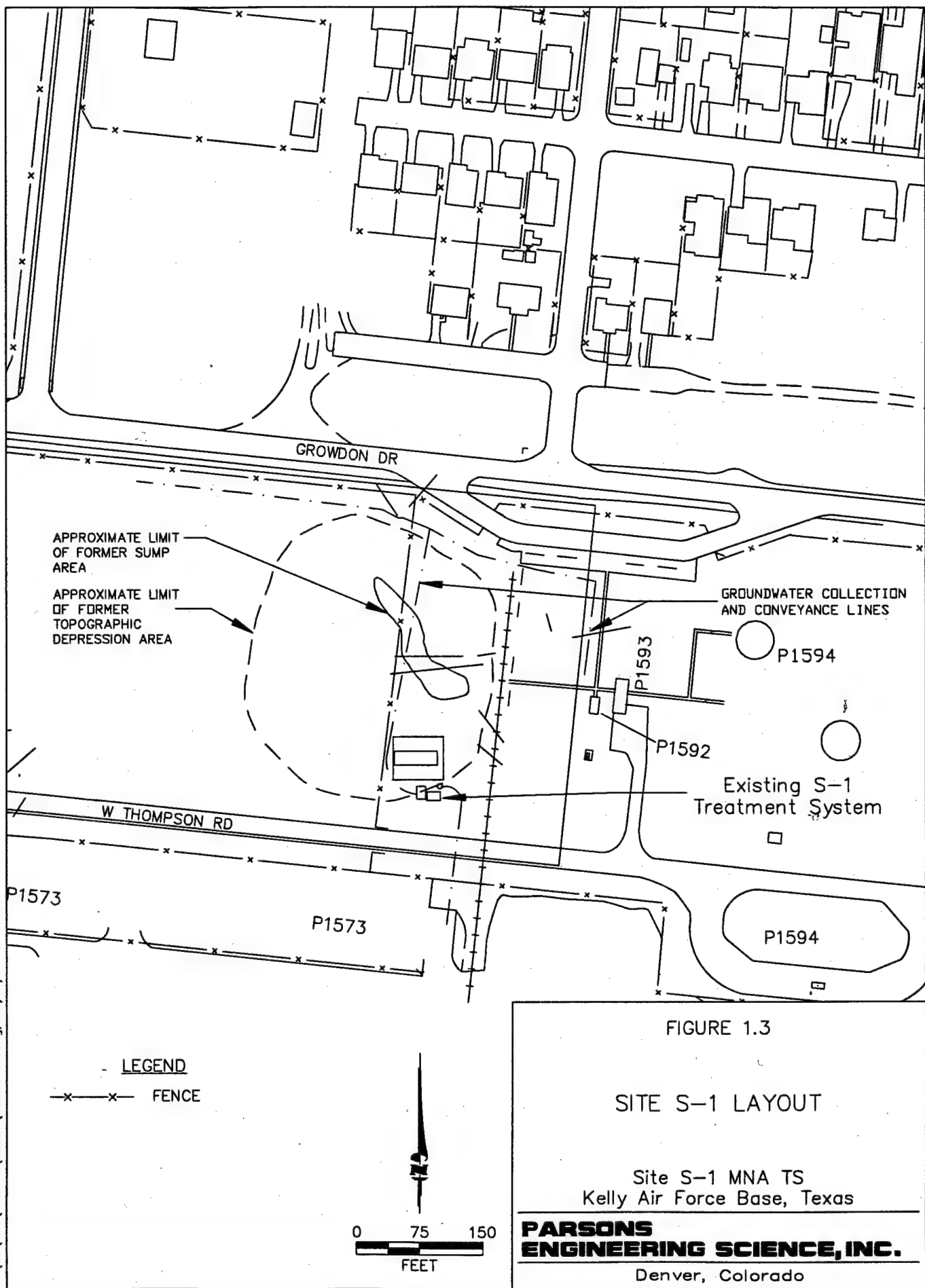
FIGURE 1.3

SITE S-1 LAYOUT

Site S-1 MNA TS
Kelly Air Force Base, Texas

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ENGINEERING SCIENCE, INC.**

Denver, Colorado

- Remedial Investigation (RI) (HNUS, 1991) -- Thirteen additional monitoring wells, 11 pumping test observation wells, 2 temporary monitoring wells, and 1 pumping well were installed. Thirty-nine groundwater samples were collected from site monitoring wells. Thirteen slug tests and one 19-hour pump test were conducted. The study recommended the installation of a groundwater extraction and treatment system to treat contaminated groundwater.

- FFS, Phase I Interim Measures (HNUS, 1994) – The purpose of this study was to design a groundwater recovery system to restrict off-base migration of shallow contaminated groundwater.

- System Performance Test Report (HNUS, 1996) – A groundwater pump-and-treat system consisting of six groundwater recovery wells and an air stripper was installed and operational by March 1995. System performance tests produced low water recovery rates, possibly due to low precipitation in the preceding 6 months. It was determined that contaminated groundwater was migrating off-base along a channel in the upper surface of the Navarro Clay.

- Final Draft FFS Report (CH2M Hill, 1997) – This report presents the interim measure system (IMS) recommended to supplement the installed remediation system and to address shallow groundwater contamination migration beyond portions of the northern and eastern Kelly AFB property boundaries.

- Basewide Operation and Maintenance Site Evaluation Technical Report (SAIC, 1997) – This report describes the work performed and the results, conclusions, and recommendations regarding potential optimization of the existing groundwater collection and treatment system at Site S-1. A primary goal of the project was to improve the recovery efficiency of the system. An additional project goal was to better delineate the contaminant source area. The long-term goal of the evaluation was to identify potential actions to enhance interim remediation system operation in order to achieve compliance with TNRCC (1996) Risk-Reduction Standards.

- Draft Site S-1 Soil FFS (CH2M Hill, 1998) - The purpose of this report was to evaluate current soil contamination at Site S-1 and to propose measures to address this contamination.

- Soil-gas survey results (Science Applications International Corp. [SAIC], 1998) - A soil-gas sampling effort in the source area was performed in February 1998 to better define locations of soil and mobile LNAPL (free product) contamination.

1.4.1 Summary of Previous Site Investigations

The installation restoration program (IRP) was initiated at Kelly AFB in 1982, and Site S-1 was designated as an IRP site. Investigations at Site S-1 began with Phase I and II IRP investigations in 1983 and 1986. A RI report for Site S-1 was prepared in 1991 (HNUS, 1991), and a focused feasibility study (FFS) was completed in 1994 for shallow groundwater remediation interim measures (HNUS, 1994). A radio frequency heating (RFH) demonstration project combined with SVE was performed in 1993 (HNUS, 1995). The purpose of the RFH/SVE demonstration was to test the enhanced recovery of volatile chlorinated and fuel compounds at Site S-1. Limited source removal was achieved, with

recommendations for additional pilot testing. An interim measure (IM) shallow groundwater recovery system consisting of 4 extraction wells and an air stripping system was installed and has been in operation since March 1995. The results of ongoing groundwater pump-and-treat system studies indicate that the current recovery well network has been unsuccessful at halting off-base contaminant migration (HNUS, 1996).

Ongoing studies at the site are being conducted by CH2M Hill and SAIC. Primary site remediation responsibility for CH2M Hill includes the completion of FFS and FS investigations and reports. The primary site remediation responsibilities for SAIC include the operation, maintenance, and optimization of the existing groundwater pump-and-treat system and limited source area delineation. A barrier wall of driven sheet piling in conjunction with a groundwater dewatering/collection trench installed in the vicinity of the existing interim pump-and-treat system has been proposed to prevent contaminated groundwater from crossing the Base boundary (SAIC, 1997). However, this remedial option recently has been reconsidered in favor of excavation and SVE in the source area. At the time of this report, CH2M Hill currently is involved with remedial design efforts for the implementation of the source excavation and SVE at Site S-1. The optimization and continued use of the interim measures pump-and-treat system will be considered after remedial actions are indicated.

SECTION 2

DATA REVIEW AND CONCEPTUAL MODEL DEVELOPMENT

To meet the objectives of the MNA TS, field investigations were conducted by Parsons ES at Site S-1 from March 24 to April 2, 1998 and from June 18 to 19, 1998. Sufficient data were collected to evaluate site hydraulics, groundwater contaminant distribution, and groundwater geochemistry and to conduct a groundwater fate and transport analysis. The significant quantity of historic data collected at the site were relied on to provide information for near-surface geology and hydrogeology. Emphasis in this study was placed on filling groundwater-related data gaps identified during previous investigations and on collecting data relevant to documenting the natural attenuation of CB compounds in groundwater.

Site characterization activities performed between March 24 and April 2, 1998 involved the placement of four additional groundwater monitoring wells (SS003MW272 to SS003MW275); groundwater sample collection from new and existing monitoring wells; collection of saturated soil for microcosm construction; analysis of groundwater and soil samples; collection and analysis of mobile LNAPL from one monitoring well; surveying of new monitoring wells and resurveying of existing Site S-1 wells; and static groundwater level measurement.

Additional site characterization performed between June 18 and 19, 1998 involved the limited collection of groundwater samples at selected Site S-1 locations; collection and analysis of mobile LNAPL at one well; and static groundwater level measurements at the wells sampled. The following sections provide an overview of the field procedures that were followed. The reader is directed to the TS Work Plan (Parsons ES, 1998) for additional details concerning field methods and techniques.

2.1 DRILLING, SUBSURFACE SOIL SAMPLING, AND CUTTINGS DISPOSAL

New soil boreholes were drilled with the goal of expanding the existing groundwater monitoring well network, collected saturated soil media for microcosm studies, and collecting additional contaminant data. Subsurface soil samples were collected at Site S-1 during soil borehole drilling. Soil samples were collected at various intervals to further delineate the nature and extent of unsaturated soil contamination at the site, and to support microcosm studies. Drilling of all boreholes and installation of wells took place between May 25 and May 30, 1998. All drilling and subsurface soil sampling and soil collection was accomplished using a hollow-stem auger (HSA) and procedures described in the work plan (Parsons ES, 1998). Table 2.1 summarizes installation details for newly installed wells and resummarizes existing well information.

TABLE 2.1
MONITORING WELL CONSTRUCTION SUMMARY
SITE S-1 MNA TS
KELLY AFB, TEXAS

IRPIMS LOCID[a]	Previous Well ID	Installation Date	Northing	Easting	Ground Elev. (ft msl)[c]	TOC[b] Elev. (ft msl)	Screened Interval Top (ft bgs)[e]	Screen Length	Bottom (ft bgs)	Total Depth (ft bgs)	Borehole Well Depth (ft bgs)	Well Diameter (inches)	Screen Slot Size (inches)	Well Status
PHASE II, STAGE 1 (RADIAN)														
SS003MW019	QQ	11/22/83	569355.99	2136924.27	690.6	694.07	25.0	10.0	35.0	35.2	40	2	0.01	ok
SS003MW020	RR	11/22/83	569205.85	2136833.15	691.5	694.70	25.0	15.0	40.0	42.0	45	2	0.01	ok
SS003MW021	VV	11/22/83	569392.32	2136594.05	689.9	693.70	25.0	5.0	30.0	32.0	35	2	0.01	ok
PHASE II, STAGE 2 (RADIAN)														
SS003MW001	S101	2/11/86	569446.82	2137174.31	690.9	690.81	22.3	11.7	34.0	34.0	40	2	0.02	ok
SS003MW002	S102	2/12/86	569096.36	2136467.14	690.5	694.28	22.5	11.5	34.0	34.0	35	2	0.02	ok
SS003MW003	S103	2/16/86	568843.04	2137584.04	689.4	692.75	24.0	10.5	34.5	34.5	40	2	0.02	ok
SS003MW004	S104	2/13/86	569207.79	2137106.22	690.6	693.19	24.5	11.0	35.5	35.5	40	2	0.02	ok
REMEDIAL INVESTIGATION (NUS)														
SS003MW005	S105	7/17/89	569490.57	2136367.08	691.9	691.51	16.7	10.3	27.0	30.1	32	2	0.01	ok
SS003MW006	S106	7/18/89	569488.59	2136855.65	690.6	690.60	17.2	10.7	27.9	31.0	37	2	0.01	often dry
SS003MW007	S107	7/18/89	569422.00	2137379.69	690.4	690.34	26.0	10.7	36.7	39.8	42	2	0.01	ok
SS003MW008	S108	7/19/89	568926.25	2137175.93	691.2	691.09	25.8	16.2	42.0	45.0	47	2	0.01	ok
SS003MW009	S109	8/1/89	569393.80	2137659.68	689.8	689.46	24.4	10.7	35.1	38.3	42	2	0.01	ok
SS003MW010	S110	8/2/89	569810.18	2137788.47	690.0	689.85	27.6	10.7	38.3	41.4	47	2	0.01	ok
SS003MW011	S111	8/3/89	569741.61	2137455.57	690.1	686.84	26.8	10.7	37.5	39.8	47	2	0.01	ok
SS003MW012	S112	8/4/89	569723.62	2138366.37	689.9	NA[g]	25.5	14.9	40.4	43.6	47	2	0.01	no longer exists
SS003MW013	S113	8/4/89	570073.65	2137505.61	690.4	690.13	27.7	16.0	43.7	46.0	52	2	0.01	does not exist
SS003MW014	S114	11/7/89	569768.76	2137170.27	689.2	688.86	16.0	14.5	30.6	33.0	37	2	0.01	ok
SS003MW015	S115	11/5/89	569419.85	2138194.99	689.7	689.51	24.8	14.5	39.3	41.7	42	2	0.01	ok
SS003MW016	S116	11/11/89	569940.75	2138345.38	690.2	690.13	23.0	15.7	38.7	42.0	47	2	0.01	ok
SS003MW017	S117	1/24/90	570396.41	2138740.93	690.7	NA	28.0	9.0	37.0	37.4	42	2	0.01	temporary well
SS003MW018	S118	1/23/90	569906.54	2136841.89	691.2	691.24	16.8	14.5	31.3	33.6	37	2	0.01	ok
SS003TW022	S119	1/24/90	570109.72	2138709.81	690.3	NA	28.0	9.5	37.5	37.9	42	2	0.01	temporary well
SS050MW002	AP02	12/19/88	569184.77	2138224.30	688.7	691.36	23.7	9.8	33.5	33.8	39	2	0.01	ok
SS050MW003	NP02	2/10/89	569185.13	2138249.14	688.4	691.15	36.7	4.9	41.7	44.0	45	2	0.01	ok
PUMP TEST WELLS (NUS)														
SS003OW032	S1-OW01	12/9/89	569450.00	2137200.00	690.0	667.75	27.3	9.7	37.0	37.0	42	2	0.01	abandoned (no pump test)
SS003OW033	S1-OW02	12/9/89	569465.00	2137214.00	690.0	667.08	24.7	9.7	34.3	34.3	42	2	0.01	abandoned (no pump test)
SS003OW034	S1-OW03	12/10/89	569480.00	2137229.00	690.0	666.64	26.5	9.7	36.2	36.2	42	2	0.01	abandoned (no pump test)
SS003OW035	S1-OW07	1/25/90	569419.38	2137394.54	690.1	689.98	27.5	9.7	37.2	44.1	42	2	0.01	abandoned after test
SS003OW036	S1-OW08	1/26/90	569405.70	2137392.69	690.1	689.96	26.6	9.4	36.0	39.7	42	2	0.01	abandoned after test

3/29/99 3:29 PM

TABLE 2.1
MONITORING WELL CONSTRUCTION SUMMARY
SITE S-1 MNA TS
KELLY AFB, TEXAS

IRPIMS LOCID	Previous Well ID	Installation Date	Northing	Easting	Ground Elev. (ft msl)	TOC Elev. (ft msl)	Screened Interval Top (ft bgs)	Screen Length	Bottom (ft bgs)	Total Depth (ft bgs)	Borehole Well Depth (ft bgs)	Well Diameter (inches)	Screen Slot Size (inches)	Well Status
SS003OW037	S1-OW09	1/26/90	569407.49	2137377.76	690.2	690.08	27.6	9.4	37.0	40.5	42	2	0.01	abandoned after test
SS003OW038	S1-OW10	1/27/90	569397.74	2137398.52	690.2	690.15	27.6	9.4	37.0	40.5	42	2	0.01	abandoned after test
SS003OW039	S1-OW11	1/27/90	569425.72	2137402.81	689.9	689.88	26.6	9.4	36.0	39.5	42	2	0.01	abandoned after test
SS003OW126	S1-OW04	12/10/89	569421.00	2137200.00	690.0	NA	24.4	10.0	34.4	34.6	42	2	0.01	abandoned (no pump test)
SS003OW127	S1-OW05	12/12/89	569422.00	2137172.00	690.0	NA	23.2	10.0	33.2	33.3	37	2	0.01	abandoned (no pump test)
SS003OW128	S1-OW06	12/13/89	569459.00	2137162.00	690.0	NA	23.0	10.0	33.0	33.1	42	2	0.01	abandoned (no pump test)
SS003PW028	S1-PW02	1/28/90	569413.64	2137386.36	690.1	689.96	23.6	13.9	37.4	43.6	47	6	0.02	abandoned (no pump test)
SS003SB125	S1-PW01	12/13/89	569435.00	2137186.00	690.0	NA	NA	NA	NA	NA	NA	NA	NA	not completed as a well
SOIL BORINGS COMPLETED AS TEMPORARY WELLS (NUS)														
SS003PW029	S1-PW03	11/5/90	569190.72	2136963.03	691.3	693.78	9.8	20.2	30.0	30.0	39	2	0.01	abandoned
SS003PW030	S1-PW04	3/12/91	569182.00	2136972.00	691.0	NA	19.0	14.5	33.5	38.9	47	6	0.02	abandoned
NA	S1-TW05	12/12/89	NA	NA	NA	NA	23.2	10.1	33.3	NA	37	2	0.01	abandoned
SS003TW049	S1-B08	4/27/91	569250.27	2136902.25	691.4	694.12	22.2	10.2	32.4	32.4	37	2	0.01	abandoned
SS003MW050	S1-B09	4/27/91	569225.61	2136926.12	691.6	694.32	22.2	9.8	32.0	32.0	37	2	0.01	ok
SS003TW051	S1-B10	4/27/91	569191.97	2136935.70	691.7	693.89	22.5	10.2	32.7	32.7	37	2	0.01	abandoned
SS003TW052	S1-B11	4/28/91	569168.27	2136954.88	691.3	691.37	19.9	10.2	30.1	30.1	32	2	0.01	abandoned
SS003MW053	S1-B12	4/28/91	569182.04	2137022.51	691.5	691.20	23.4	10.2	33.6	33.6	37	2	0.01	ok
GROUNDWATER RECOVERY WELLS														
KY029MW001	1501	7/29/92	569158.00	2136426.00	691.1	690.36	11.5	15.0	26.5	27.5	NA	2	0.01	ok
KY029MW002	1502	7/30/92	569182.00	2136546.00	692.6	692.05	15.0	20.0	35.0	35.0	NA	2	0.01	ok
KY029MW003	1503	7/30/92	569090.54	2136601.88	691.9	691.23	15.0	20.0	35.0	35.0	NA	2	0.01	ok
KY029MW004	1504	7/29/92	569027.00	2136481.00	692.6	691.77	12.5	15.0	27.5	27.5	NA	2	0.01	ok
KY029MW005	NA	11/15/95	569082.80	2136494.00	691.4	690.29	11.3	25.0	36.3	39.0	NA	2	0.01	ok
KY029MW006	NA	11/16/95	569128.50	2136510.00	691.5	691.07	7.3	25.0	32.3	35.0	NA	2	0.01	ok
SS003MW025	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
SS003MW026	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
SS003MW027	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	does not exist
SS003MW050	S1-B09	4/27/91	569225.43	2136926.12	691.6	691.25	22.2	9.8	32.0	32.0	NA	2	0.01	ok
SS003MW108	MW-1	1/13/95	569371.63	2136665.56	690.4	690.08	12.9	15.0	27.9	29.9	NA	2	0.01	ok
SS003MW109	MW-2	1/24/95	569354.64	2136825.74	691.1	690.72	18.1	10.0	28.1	30.1	NA	2	0.01	ok
SS003MW110	MW-3	1/26/95	569316.47	2136970.61	691.6	691.24	19.1	15.0	34.1	36.1	NA	2	0.01	ok
SS003MW119	DW-1	NA	569186.05	2137008.99	691.6	691.46	NA	NA	NA	NA	NA	NA	NA	ok
SS003MW120	DW-2	NA	569134.33	2136958.91	691.0	690.82	NA	NA	NA	NA	NA	NA	NA	ok

TABLE 2.1
MONITORING WELL CONSTRUCTION SUMMARY
SITE S-1 MNA TS
KELLY AFB, TEXAS

IRPIMS LOCID[a]	Previous Well ID	Installation Date	Northing	Easting	Ground Elev. (ft msl)[c]	TOC[b] Elev. (ft msl)	Screened Interval Top (ft bgs)[d]	Screen Length	Bottom (ft bgs)	Total Depth (ft bgs)	Borehole Well Depth (ft bgs)	Well Diameter (inches)	Screen Slot Size (inches)	Well Status
SS003MW121	DW-3	NA	569129.00	2137007.78	691.3	691.17	NA	NA	NA	NA	NA	NA	NA	ok
SS003MW272	NA	3/26/98	569184.57	2136949.26	691.8	691.55	20.5	10.0	30.5	31.5	31.5	2	0.01	ok
SS003MW273	NA	3/25/98	569280.28	2137030.14	692.0	691.39	22.0	10.0	32.0	34.0	34.0	2	0.01	ok
SS003MW274	NA	3/26/98	569243.39	2136965.89	691.7	691.11	21.0	10.0	31.0	32.0	32.0	2	0.01	ok
SS003MW275	NA	3/28/98	569039.39	2136809.97	690.7	690.37	16.5	10.0	26.5	27.5	34.0	2	0.01	ok
SS003RW111	RW-1	1/20/95	569392.22	2136607.89	690.3	688.09	18.4	10.0	28.4	33.4	NA	6	0.01	ok
SS003RW112	RW-2	1/20/95	569379.82	2136727.51	690.1	688.00	13.3	15.0	28.3	33.3	NA	6	0.01	ok
SS003RW113	RW-3	1/23/95	569348.76	2136923.64	691.1	689.18	19.1	15.0	34.1	39.1	NA	6	0.01	ok
SS003RW114	RW-4	1/23/95	569305.15	2137011.64	691.7	685.59	19.7	19.8	39.5	44.5	NA	6	0.01	ok
SS003RW115	RW-5	1/20/95	569274.54	2137149.21	691.1	688.95	18.0	15.0	33.0	38.0	NA	6	0.01	ok
SS003RW116	RW-6	1/18/95	569163.38	2137136.48	691.1	688.9	18.4	15.0	33.4	38.4	NA	6	0.01	ok
SS003RW202	NA	8/1/97	569315.84	2137014.80	691.6	691.0	23.5	10.0	33.5	38.5	NA	4	0.07	ok
SS050MW156	MW-85	9/27/95	570185.24	2136575.70	693.0	692.8	19.5	15.0	34.5	37.0	19.5	2	0.01	ok
SS050MW157	MW-86	10/23/95	570707.14	2137250.39	692.6	692.3	22.0	15.0	37.0	39.0	22.0	2	0.01	ok
SS050MW159	MW-88	9/28/95	570644.14	2137834.97	691.5	691.2	22.5	15.0	37.5	40.3	22.5	2	0.01	ok

[a] IRPIMS LOCID = Installation Restoration Program Information Management System Location Identification.

[b] TOC = top of casing.

[c] ft msl = Feet above mean sea level.

[d] ft bgs = Feet below ground surface.

[e] NA = Not available.

Ten subsurface samples were collected from 6 of 10 new soil boreholes. Figure 2.1 shows the location of each of these subsurface soil sampling locations. Table 2.2 presents sample intervals for each of the May 1998 subsurface sampling locations (sample coordinates are included in Appendix A). This table also lists the field and fixed-base laboratory analytical methods used to evaluate each of the soil samples. Four of the 10 new soil boreholes were completed as permanent, 2-inch-diameter groundwater monitoring wells (SS003MW272 to SS003MW275). The wells were completed as per technical well specifications for Kelly AFB (SA-ALC, 1994). Five of the new soil borings were drilled to groundwater in order to collect microcosm media (Section 2.2). The boreholes were abandoned with a bentonite/cement mixture to within a few feet of the ground surface. Two soil borings were abandoned due to the absence of water above the lower Navarro Formation (SS003SB271) or refusal of the drilling rig due to coarse gravel (SS003SB276). Soil borings SS003SB277 through SS003SB279 were placed near existing wells SS003MW50, SS003MW001, SS003MW016, respectively, to collect soil microcosm materials from locations with previously defined groundwater contaminant concentrations.

Borehole logs, well completion diagrams, well development records, and survey data are included in Appendix A. Geological data are presented in Section 3 to characterize the physical setting of the site. Analytical results for soil are used in Section 4 to characterize the nature and extent of soil contamination at the site.

Soil cuttings generated during field work were stored in appropriately labeled 55-gallon drums. Soil cuttings were generated from the following soil boring and monitoring well locations: SS003SB271, -276 to -280, and -272 to -275. The soils were transported on March 28th and 30th to a Base-designated and secured soil staging laydown yard. Samples of the drum contents were collected after completion of the field work and submitted to Quanterra Environmental Laboratories in Denver, Colorado. The drum samples were analyzed for leachability using methods toxicity characteristic leaching procedure (TCLP)-SW8260A and TCLP-SW8270B, TCLP for RCRA 8 Metals, and for total petroleum hydrocarbons (TPH) using method E418.1. The drum samples were disposed of by Kelly AFB personnel to the Covel Gardens Landfill in San Antonio.

2.2 MICROCOSM SAMPLING

Microcosm experiments were performed as part of this study to verify observed trends in microbial transformation at Site S-1. Little is known about field biodegradation rates of mixed chlorinated benzenes under aerobic and anaerobic conditions. For instance, it is still uncertain whether CB can degrade anaerobically through the process of reductive dechlorination which can occur in the highly reduced portions of a contaminant plume. Although CB is known to degrade aerobically, degradation occurs more rapidly when indigenous microorganisms have acclimated to dissolved CB concentrations. This acclimation period may take more than a year and, therefore, aerobic CB degradation may be less effective on transient groundwater plumes whose CB concentrations are largely seasonally dependent. Highly reducing conditions at Site S-1 source area and aerobic conditions at the periphery of the groundwater plume provide the environment required to study all possible chlorobenzene transformation processes and their potential effects on applied natural attenuation. Details regarding microcosm study results are described in Section 4.8.

FIGURE 2.1

SAMPLING LOCATIONS

Site S-1 MNA TS
Kelly Air Force Base, Texas

**PARSONS
ENGINEERING SCIENCE, INC.**
Denver, Colorado

LEGEND

MONITORING WELL
"RW" IDENTIFIER INDICATES
A RECOVERY WELL

SOIL BOREHOLE

FENCE

FEET
0   100   200   400
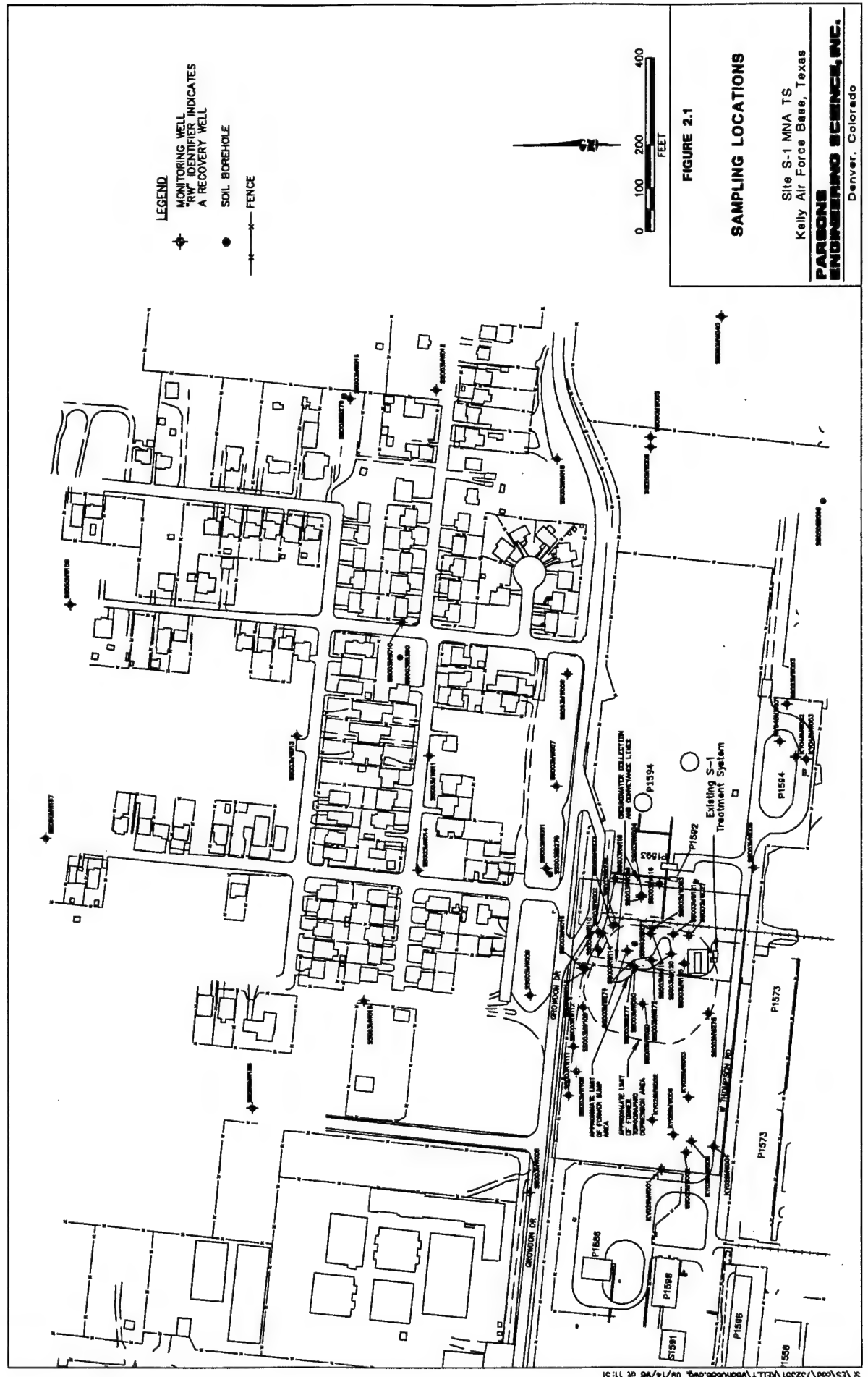
TABLE 2.2
ANALYTICAL METHOD SUMMARY
SITE S-1 MNA TS
KELLY AIR FORCE BASE, TEXAS

LOCID	VOCs[a] (SW8260A)	Nitrate (SW9056)	Nitrite (E300)	Sulfate (SW9056)	Chloride (SW9056)	Alkalinity (E310.1)	Dissolved Organic Carbon (SW9060)	Methane, Ethane, Ethene (RSK175)	SVOCs[b] (SW8270B)	Total Dissolved Solids (E160.1)	Chemical Oxygen Demand (E410.4)	Hardness (E130.2)	Total Metals (SW6010A)	TPH (E418.1)	Cyanide (SW9012)	Total Organic Carbon (SW9060)	Density (D5057)
GROUNDWATER																	
SS003MW001	x	x	x	x	x	x	x	x	x								
SS003MW004	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
SS003MW007	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
SS003MW008	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
SS003MW009	x								x								
SS003MW010	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
SS003MW011	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
SS003MW013	x	x	x	x	x	x	x	x	x							x	
SS003MW016	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
SS003MW018	x	x	x	x	x	x	x	x	x	x	x	x		x	x		
SS003MW019	x	x	x	x	x	x	x	x	x								
SS003MW020	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
SS003MW050	x	x	x	x	x	x	x	x	x							x	
SS003MW053	x	x	x	x	x	x	x	x	x								
SS003MW109	x	x	x	x	x	x	x	x	x		x						
SS003MW110	x	x	x	x	x	x	x	x	x								
SS003MW115	x	x	x	x	x	x	x	x	x								
SS003MW116	x	x	x	x	x	x	x	x	x								
SS003MW120	x	x	x	x	x	x	x	x	x								
SS003MW121	x	x	x	x	x	x	x	x	x	x	x						
SS003MW202	x	x	x	x	x	x	x	x	x								
SS003MW272	x	x	x	x	x	x	x	x	x								
SS003MW273	x	x	x	x	x	x	x	x	x								
SS003MW274	x	x	x	x	x	x	x	x	x								
SS003MW275	x	x	x	x	x	x	x	x	x								
FREE PRODUCT																	
SS003RW114	x								x					x			x
SS003MW272	x								x					x			x
SOIL																	
SS003MW272SB (16 to 16.5)[c]	x																
SS003MW272SB (27 to 27.4)	x																
SS003MW273SB (16 to 16.5)	x																
SS003MW273SB (30 to 30.1)	x																
SS003MW274SB (15 to 16)	x																
SS003MW274SB (30 to 31)	x																
SS003MW275SB (16.5 to 17)	x																
SS003MW275SB (25.5 to 26)																x	
SS003SB277 (30 to 33)	x																
SS003SB278 (29 to 30)	x																

Note: Shaded area indicates a measurement not collected.

[a] VOCs = volatile organic compounds.

[b] SVOCs = semivolatile organic compounds.

[c] Sample depth in feet below ground surface.

Attempts to collect microcosm materials occurred from March 24 to 27, 1998. Saturated soils were collected with a 2-inch inside diameter (ID) split spoon sampler; Shelby tubes were not used for materials collection as originally specified in the work plan (Parsons ES, 1998) because of the presence of gravel and cobbles that crushed the Shelby assembly. Split-spoon samplers used in place of Shelby tubes also were affected by gravelly conditions in the saturated zone and soil recovery was limited. A sufficient quantity of soil microcosm materials was extracted from a single soil boring at SS003MW272 to set-up an anaerobic microcosm study. Materials collected at this location were immediately transferred from the split-spoon sampler and transferred to four, 8-ounce Teflon®-lined sampling jars. Sufficient saturated soils for anaerobic soil microcosm materials could not be successfully collected at locations SS003SB271, SS003SB276, SS003MW274, and SS003SB277. Dr. Jim Gossett of Cornell University provided oversight for the anaerobic microcosm sampling phase of the field work.

Materials collected for aerobic microcosms consisted of groundwater, disturbed well sediments, and/or saturated soils collected during drilling operations. Groundwater with disturbed sediments was collected at SS003MW002, located upgradient from Site S-1, and at SS003MW001 downgradient from the source area. Aerobic microcosm materials also were collected 75 feet west of SS003MW010 at a depth of approximately 36 feet below ground surface (bgs) in the center of an abandoned housing lot (Figure 2.1). Several ounces of saturated aquifer sediments were extracted at this location with a 2-inch ID split-spoon sampler and combined with 1 gallon of groundwater collected from SS003MW010. Drilling operations were halted by the presence of coarse gravel/cobbles near monitoring well SS003MW016 and microcosm samples were not collected at this location. Dr. Jim Spain of Tyndall AFB, Florida provided 0.5-gallon containers to hold the microcosm sediments and liquids and provided oversight for the collection of aerobic microcosm materials.

2.3 GROUNDWATER SAMPLING

Parsons ES collected a total of 25 groundwater samples at 25 shallow monitoring and recovery wells between March 24 and April 2, 1998. Wells sampled in this event included: SS003MW001, SS003MW018, SS003MW007, SS003MW008, SS003MW009, SS003MW010, SS003MW011, SS003MW013, SS003MW016, SS003MW018, SS003MW019, SS003MW020, SS003MW050, SS003MW053, SS003MW109, SS003MW110, SS003RW115, SS003RW116, SS003MW120, SS003MW121, SS003RW202, SS003MW272, SS003MW273, SS003MW274, SS003MW275. Groundwater quality and geochemical data were collected at these wells to verify trends in natural chemical attenuation over time. All collected groundwater samples were analyzed for VOCs using method SW8260A in order to measure chlorobenzenes, chlorinated ethenes, and other fuel constituents. Other necessary geochemical and chemical parameters required to document natural attenuation also were collected as listed in Table 2.2. The 1998 groundwater data are presented in Section 4.

Additional groundwater analysis beyond the scope of this TS were performed on 10 of the above groundwater samples at the request of the SA-ALC Environmental Management Restoration Organization (EMRO). The additional analyses were performed at monitoring wells that both were sampled in this study and selected for annual sampling in June 1998 as part of the annual groundwater monitoring program at Kelly AFB. The additional analytical parameters performed on the 10 samples were:

dissolved organic carbon (SW9060), semivolatile organic compounds (SVOCs) (SW8270B), total dissolved solids (E160.1), chemical oxygen demand (COD) (E410.4), hardness (E130.2), total metals (SW6010A), cyanide (SW9012), and TOC (SW9060). Table 2.2 identifies the locations at which these analysis were performed.

Groundwater samples collected on June 18 and 19, 1998 were analyzed for VOCs by method SW8260A. The following wells were sampled: SS003MW001, SS003MW008, SS003MW010, SS003MW016, SS003MW050, SS003MW053, SS003MW053, SS003MW120, and SS003MW274. These wells were resampled to obtain additional resolution of potential chlorinated ethene and BTEX contamination in the source areas at levels that were below the analytical reporting limits for the March/April 1998 samples. Additional groundwater samples also were collected at locations beyond the source area during the June 1998 sampling event to help define the contaminant plume.

2.4 LNAPL SAMPLING

The only location where LNAPL was detected between March 24 and April 2, 1998 was in the main 4-inch ID recovery well at SS003RW114. A disposable bailer was used to pull the dark product to the surface and transfer the liquid to a 40-milliliter (mL) VOA bottles for laboratory analysis. The LNAPL sample was sampled for VOCs, SVOCs, TPH, and density using methods SW8260A, SW8270B, E418.1, and ASTM-D5057, respectively.

LNAPL was detected in four monitoring wells in June 1998, including SS003MW053, SS003MW120, SS003MW273, and SS003MW274. Monitoring well SS003RW114 was not remeasured for LNAPL thickness. An LNAPL sample was collected from SS003MW272 and analyzed using the same analytical methods described above for SS003RW114. The results of LNAPL sampling are discussed in Section 4.

2.5 GROUNDWATER LEVEL MEASUREMENTS

The depth of the groundwater surface below the top of the well casing was measured at 37 monitoring wells on- and off-base to determine the flow characteristics of the aquifer (Section 3). Groundwater measurements were performed by lowering an electronic groundwater level probe into the well and measuring the groundwater level relative to the north side of the top of the casing. Groundwater elevations also were measured in the sampled wells during the June 1998 sampling event.

2.6 SURVEYING

After completion of field work, the locations and elevations of all new monitoring wells, soil boring locations, and numerous pre-existing monitoring wells were surveyed by Baker Surveying & Engineering, Inc., which is a licensed land surveying company from San Antonio, Texas. The horizontal locations and elevations of the measurement datum (top of PVC well casing), the ground surface adjacent to the well casing, the rim of the protective well box, and the edge of the concrete pad were measured relative to existing control points referenced to datum NAD27. Horizontal locations were surveyed to the nearest 0.1 foot. Measurement datum and ground surface elevations were surveyed to the nearest 0.01 foot. Survey data are presented in Table 2.1 and Appendix A.

SECTION 3

PHYSICAL CHARACTERISTICS OF THE STUDY AREA

This section describes the physical characteristics of Site S-1 as determined from data collected by Parsons ES in March/April 1998 and June 1998 and from pertinent data available in previous site reports (see Section 1.4)

3.1 TOPOGRAPHY, SURFACEWATER HYDROLOGY, AND CLIMATE

Ground surface elevations at Kelly AFB range from 730 feet above mean sea level (msl) along the western border of the Base to 620 feet msl along the southern boundary of the Base (HNUS, 1991). Site S-1 is generally flat, with surface elevations ranging from 690 to 691 feet msl. The site is covered with grass except in the area of a 150- by 300-foot former depression (Figure 1.3), now filled in with dark brown to black gravelly clay containing sand and silt. The fill also contains trash, broken glass, wire, metal fragments, plastic, cans, wood fragments, and concrete rubble. The fill is approximately 25 feet thick at the center of the former depression.

Surface water throughout most of Kelly AFB drains by a combination of ditches, swales, and storm sewers that ultimately discharge to Leon Creek, which enters the Base near the intersection of Billy Mitchell Road and Westover Road (Figure 1.2). Leon Creek flows south-southeast across the Base and passes under Military Drive near the southern end of the Base. The closest stretch of Leon Creek to Site S-1 is near Billy Mitchell Road and Westover Road approximately 10,000 feet distant. Surface water from Site S-1 flows off-base to the northeast, toward Apache Creek, approximately 2.5 miles away. Precipitation at Site S-1 is prone to ponding at various locations within the fenced area. However, much of the surficial gravel fill within the fenced area allows rapid infiltration during rainfall events.

The climate of San Antonio is continental to subtropical (SAIC, 1997). This climate can be characterized as having two seasons: dry, mild winters, and hot, humid summers. Average annual temperature is 69 degrees Fahrenheit (°F). The month average ranges from a January mean temperature of 52°F to a July and August mean of 84°F. Average annual rainfall is 29 inches, most of which occurs from April through October. Average annual evaporation from shallow lakes, as reported by the National Weather Service, is 58 inches. Winds are generally from the north during October through February, and prevailingly from the southeast during March through September.

3.2 REGIONAL GEOLOGY AND HYDROGEOLOGY

Kelly AFB is located in the Gulf Coastal Plain physiographic province, a region of gently rolling plains and moderate hills. Regional geology is characterized by clays,

marls, sands, and limestones of a thick stratigraphic sequence of Quaternary alluvial sediments underlain by the more than 400-foot-thick Upper Cretaceous Navarro Clay (HNUS, 1991).

There are two main aquifers beneath Kelly AFB; the unconfined shallow alluvial aquifer and the confined Edwards Aquifer. The aquifers are separated by the Navarro Clay Group. There does not appear to be any hydraulic connection between the two aquifers in the vicinity of Kelly AFB. The shallow aquifer overlying the Navarro Clay is composed of alluvial coarse-grained sand and clayey gravel. Groundwater flow within the alluvial aquifer is influenced by the distribution of coarse-grained channels overlying the surface of the Navarro Group and by the topography of the Navarro Formation itself. The alluvial aquifer is dry in areas where the Navarro clays extend above the water table because the Navarro Clay has a very low permeability to groundwater flow.

3.3 SITE S-1 GEOLOGY AND HYDROGEOLOGY

Site S-1 geology is characterized by an alluvial and fill layer from 27 to 34 feet thick atop the Navarro Formation. The top 5 to 25 feet of the unconsolidated deposits consists of black-brown to reddish-brown clay with trace amounts of caliche granules, silt, and fine sand. Much of this material at Site S-1 was fill material used to fill the former sump area depression. The lithology between the upper clay zone and the Navarro Formation is a clayey gravel and gravel sequence with occasional thin sand layers. The thin, geologically complex alluvial aquifer is primarily composed of basal gravel and clayey gravel that are the most common water-bearing units. The gravels are bounded vertically (and laterally in places) by the Navarro Formation. Figure 3.1 shows the locations of two hydrogeologic profiles constructed for the site. The cross sections are presented in Figures 3.2 and 3.3.

The surface of the Navarro Group slopes to the northeast/north through the site and has a vertical permeability of approximately 1.3×10^{-8} centimeters per second (cm/sec) (HNUS, 1994). Figure 3.4 shows an conceptualized surface of the Navarro Formation compiled from previous reports (NUS, 1994; SAIC, 1997; CH2M Hill, 1998) and current boring logs (Appendix A). Data used for Figure 3.4 is summarized in Table 3.1. The surface of the Navarro Formation decreases in elevation from approximately 558 to 662 feet msl to approximately 646 feet msl between the source area and downgradient monitoring well SS003MW016. A high density of soil borings drilled in the source area indicates that the Navarro surface at this location is characterized by rises and depressions that may affect groundwater flow. This subject is discussed in greater detail in the next subsection.

3.3.1 Groundwater Hydraulics

The depth to shallow groundwater ranges from approximately 20 feet bgs to the southeast of the site at monitoring well SS003MW008 to approximately 32 feet bgs at recovery well SS003RW115. The substantial drop in groundwater elevation near this

FIGURE 3.1

CROSS-SECTION
LOCATION MAP

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.

Denver, Colorado

Source: CH2M Hill, 1998.

LEGEND

Gravel Fill
Clay/Clay Fill
Gravel
Silt
Navarro Clay
EOB = End of Boring
Water Table
200 Soil Sample Chlorobenzene Concentration (ppm)

Horizontal Scale in Feet
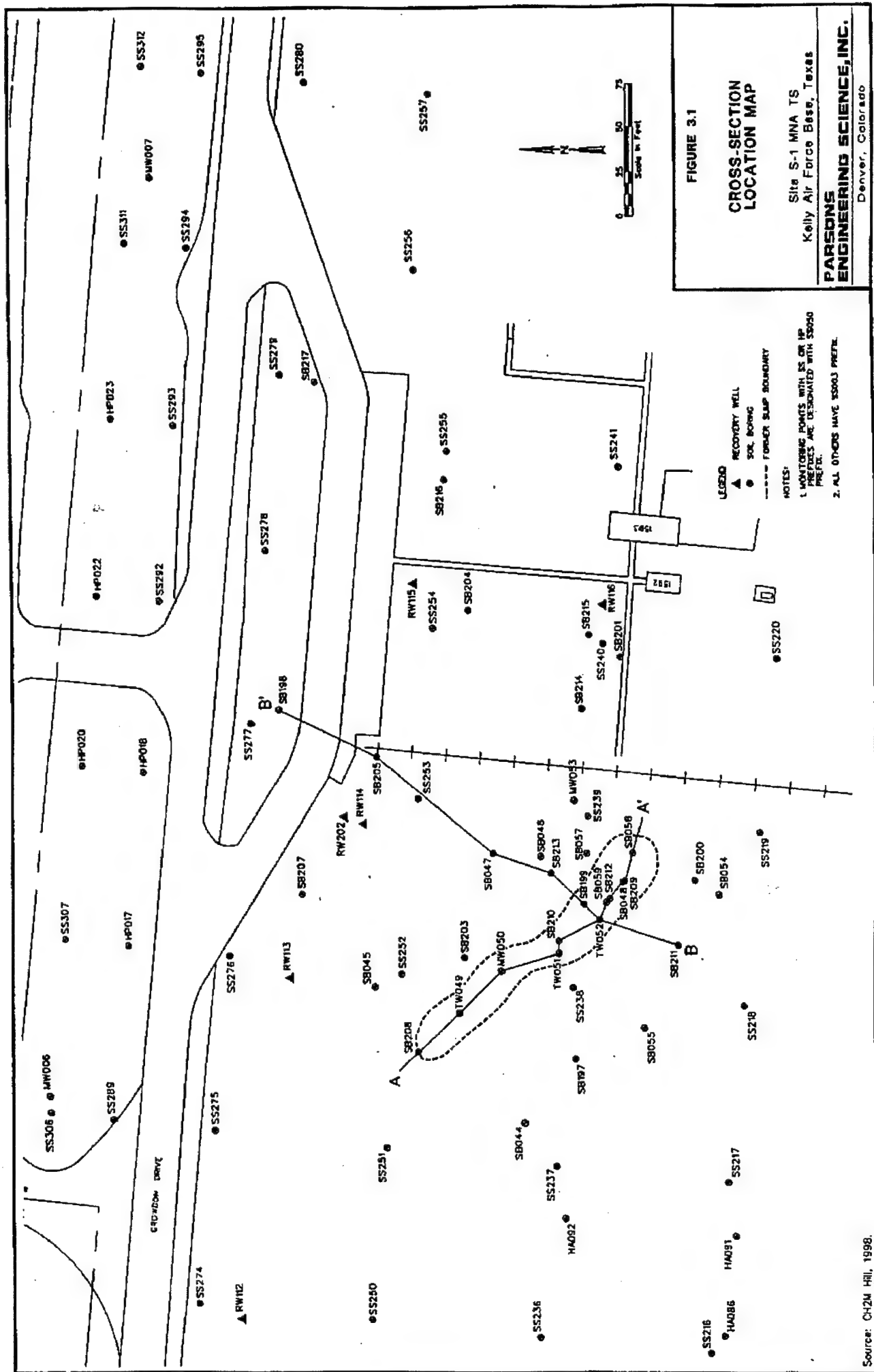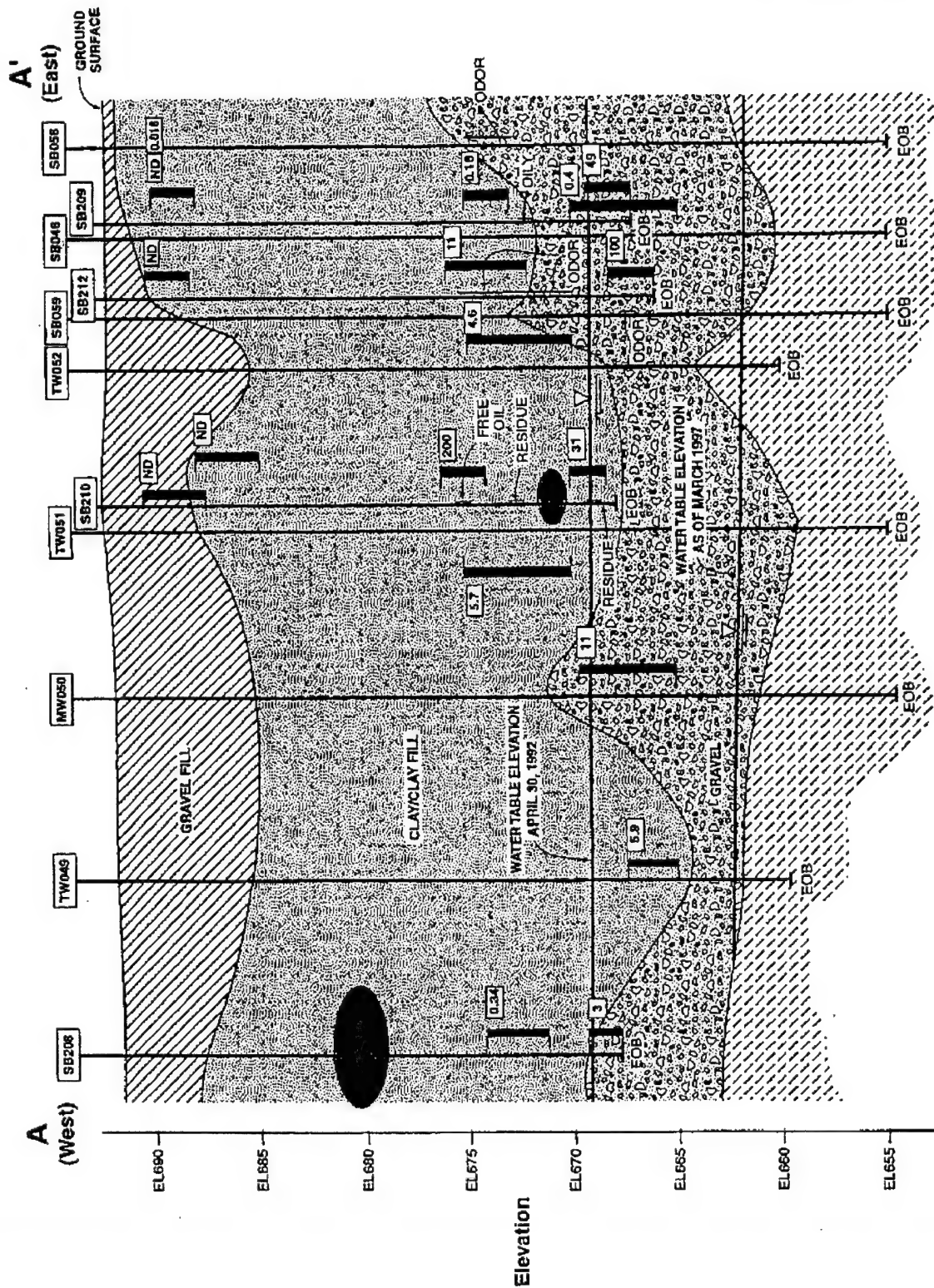
FIGURE 3.2

GEOLOGIC CROSS-SECTION
A-A'

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado

Source: CH2M Hill, 1998.

FIGURE 3.3

GEOLOGIC CROSS-SECTION
B-B'

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.

Denver, Colorado

Source: CH2M Hill, 1996.

LEGEND

+ MONITORING WELL LOCATION

● BOREHOLE SAMPLE LOCATION

×—× FENCE

—(660)— INFERRED LINE OF EQUAL NAVARRO FORMATION SURFACE ELEVATION IN FEET ABOVE MEAN SEA LEVEL (MSL)

FIGURE 3.4

NAVARRO FORMATION SURFACE ELEVATIONS

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado

TABLE 3.1
NAVARRO FORMATION ELEVATIONS
SITE S-1 MNA TS
KELLY AIR FORCE BASE, TEXAS

Former LOCID	Current LOCID	Easting	Northing	Navarro Surface Elevation (feet msl)[a]
SB198	SB198	2137073.28	569361.89	657.0
SB201	SB201	2137098.85	569147.49	661.5
SB205	SB205	2137046.57	569299.72	658.0
S101	SS003MW001	2137174.31	569446.82	656.6
S102	SS003MW002	2136467.14	569096.36	658.1
S103	SS003MW003	2137584.04	568843.04	656.3
S104	SS003MW004	2137106.22	569207.79	657.8
S105	SS003MW005	2136367.08	569490.57	664.6
S105	SS003MW005	2136367.08	569490.57	664.6
s106	SS003MW006	2136855.65	569488.59	660.4
S107	SS003MW007	2137379.69	569422.00	654.1
S108	SS003MW008	2137175.93	568926.25	650.6
S109	SS003MW009	2137659.68	569393.80	656.7
S110	SS003MW010	2137788.47	569810.18	647.9
S111	SS003MW011	2137455.57	569741.61	652.3
S113	SS003MW013	2137505.61	570073.65	644.2
S114	SS003MW014	2137011.64	569305.15	658.2
S115	SS003MW015	2138194.99	569419.85	652.5
S116	SS003MW016	2138345.38	569940.75	647.0
S118	SS003MW018	2136839.79	569909.06	656.9
qq	SS003MW019	2136924.27	569355.99	656.6
v v	SS003MW021	2136594.05	569392.32	662.3
S1B09	SS003MW050	2136926.12	569225.43	656.5
S1B12	SS003MW053	2137022.51	569182.04	658.0
MW120	SS003MW120	2136958.91	569134.33	659.5
MW121	SS003MW121	2137007.78	569129.00	660.0
SS003MW274	SS003MW274	2136965.89	569243.39	660.2
S1B08	SS003TW049	2136903.39	569249.64	658.0
S1B10	SS003TW051	2136930.82	569192.24	655.0
S1B11	SS003TW052	2136951.21	569168.59	658.5
SB197	SB197	2136878.93	569186.45	653.5
SB01	SB01	2136845.24	569217.19	664.3
SB03	SB03	2136990.75	569201.22	657.4
RW202	RW202	2137014.80	569315.84	657.5
SB047	SB047	2136992.82	569230.16	659.0
SB02	SB02	2136929.66	569316.47	660.3
S1B18	S1B18	2136960.11	569160.23	656.0
S1B06	S1B06	2136974.32	569154.97	655.0
S1B17	S1B17	2136989.98	569149.52	657.0

[a] feet msl = Feet above mean sea level.

well cannot be explained by variations in the Navarro Formation and is likely due to groundwater pumping from recovery wells SS003RW114, -RW115, and -RW116. Groundwater elevations collected on April 2, 1998 and June 18 to 19, 1998 are shown in Table 3.2.

3.3.1.1 Groundwater Flow Direction and Gradient

Groundwater elevations measured at Site S-1 in April to June 1998 are shown on Figures 3.5 and 3.6, respectively. Groundwater elevations primarily are affected by three physical characteristics of the site: 1) the slope of the underlying Navarro Formation; 2) channeling of the thin water table in the source area; and 3) the groundwater pump-and-treat system. Groundwater elevations follow the general trend of the Navarro Formation surface as it slopes to the north/northeast (Figure 3.4).

Numerous interpretations of the Navarro surface have been developed in past reports as soil boring data have become available through previous investigations (Halliburton HNUS, 1991 & 1996; SAIC, 1997; and CH2M Hill, 1998). These interpretations indicate that groundwater flow from the former sump area toward the northeast is influenced by a corridor created by portions of the Navarro Formation that rise above the water table. The corridor acts as a preferential groundwater migration pathway. The phenomenon is best supported by Figure 3.4 and by the Navarro Clay surface interpretation created by HNUS (1996) that is included in Appendix A. A comparison of Figures 3.4 and 3.5 suggests that the Navarro Formation extends above the groundwater table at several locations northwest of the former sump area and extends to near the water table southeast of the former sump. Therefore, it is plausible that groundwater is physically channeled in the source area due to the topography of the Navarro surface. However, the unsaturated and minimally saturated portions of the alluvial aquifer appear to be very localized, and approximately six feet of water was present above the Navarro Formation throughout most of the former sump area in April 1998. In addition, neither of the water table maps constructed for the site indicate groundwater channeling (Figures 3.5 and 3.6).

The groundwater table over recent years has been affected by an array of groundwater extraction wells positioned to intercept groundwater contamination that is migrating from Site S-1. Figure 3.7 depicts the March 1995 groundwater table prior to the start-up of groundwater pump-and-treat operation. Comparison of Figures 3.5 (April 1998 contours), 3.6 (June 1998 contours), and 3.7 (March 1995 contours) shows that saturated thickness of the alluvial aquifer has been reduced downgradient from the source area, primarily near recovery wells SS003RW114 and SS003RW115. Historically, nearly fifty percent of the flow from the pump-and-treat system has been from monitoring well SS003RW114 (SAIC, 1997) (Table 3.3). However, the current position of the water table depression indicates that recovery well SS003RW115 also is substantially influencing the groundwater table, although low groundwater recovery rates at this location do not support this observation. The average total groundwater extraction rate from the pump-and-treat system was 1,350 gallons per day (gpd) (derived from Table 3.3). Approximately 648 gpd, or 48 percent of the total pumping rate, was extracted from recovery wells SS003RW114 and SS003RW115.

TABLE 3.2
GROUNDWATER ELEVATIONS
SITE S-1 MNA TS
KELLY AFB, TEXAS

IRPIMS LOCID[a]	Date	Ground Surface Elevation (ft msl)[b]	TOC Elevation (ft msl)	Screened Interval Top (ft bgs)[c]	Screen Length	Bottom (ft bgs)	Water Level (ft btoc)[d]	Free Product (inches)	Corrected Water Level[e] (ft btoc)	Groundwater Elevation (ft msl)
KY029MW003	1-Apr-98	691.19	691.09	15.0	20.0	35.0	25.61	NA[f]	25.61	665.48
SS003MW001	1-Apr-98	690.88	690.81	22.3	11.7	34.0	30.28	NA	30.28	660.53
SS003MW001	18-Jun-98	690.88	690.81	22.3	11.7	34.0	30.86	NA	30.86	659.95
SS003MW002	1-Apr-98	690.52	694.28	22.5	11.5	34.0	27.39	NA	27.39	666.89
SS003MW003	1-Apr-98	689.43	692.75	24.0	10.5	34.5	30.51	NA	30.51	662.24
SS003MW004	1-Apr-98	690.62	693.19	24.5	11.0	35.5	31.71	NA	31.71	661.48
SS003MW005	1-Apr-98	691.90	691.51	16.7	10.3	27.0	24.46	NA	24.46	667.05
SS003MW007	1-Apr-98	690.41	690.34	26.0	10.7	36.7	29.80	NA	29.80	660.54
SS003MW008	1-Apr-98	691.19	691.09	25.8	16.2	42.0	20.02	NA	20.02	671.07
SS003MW008	18-Jun-98	691.19	691.09	25.8	16.2	42.0	29.42	NA	29.42	661.67
SS003MW009	1-Apr-98	689.78	689.46	24.4	10.7	35.1	36.88	NA	36.88	652.58[g]
SS003MW010	1-Apr-98	690.03	689.85	27.6	10.7	38.3	29.80	NA	29.80	660.05
SS003MW010	18-Jun-98	690.03	689.85	27.6	10.7	38.3	30.86	NA	30.86	658.99
SS003MW011	1-Apr-98	690.11	689.84	26.8	10.7	37.5	29.62	NA	29.62	660.22
SS003MW013	1-Apr-98	690.43	690.13	27.7	16.0	43.7	30.14	NA	30.14	659.99
SS003MW015	1-Apr-98	689.71	689.51	24.8	14.5	39.3	29.80	NA	29.80	659.71
SS003MW016	1-Apr-98	690.22	690.13	23.0	15.7	38.7	30.68	NA	30.68	659.45
SS003MW016	18-Jun-98	690.22	690.13	23.0	15.7	38.7	31.49	NA	31.49	658.64
SS003MW018	1-Apr-98	691.25	691.24	16.8	14.5	31.3	31.09	NA	31.09	660.15
SS003MW019	1-Apr-98	690.61	694.07	25.0	10.0	35.0	32.87	NA	32.87	661.20
SS003MW020	1-Apr-98	691.51	694.70	25.0	15.0	40.0	28.23	NA	28.23	666.47
SS003MW021	1-Apr-98	689.93	693.70	25.0	5.0	30.0	28.31	NA	28.31	665.39
SS003MW050	1-Apr-98	691.62	691.25	22.2	9.8	32.0	26.97	NA	26.97	664.28
SS003MW050	18-Jun-98	691.62	691.25	22.2	9.8	32.0	27.97	NA	27.97	663.28
SS003MW053	1-Apr-98	691.50	691.20	23.4	10.2	33.6	28.01	NA	28.01	663.19
SS003MW053	18-Jun-98	691.50	691.20	23.4	10.2	33.6	29.50	sheen	29.50	661.70
SS003MW108	1-Apr-98	690.39	690.08	12.9	15.0	27.9	24.49	NA	24.49	665.59
SS003MW109	1-Apr-98	691.14	690.72	18.1	10.0	28.1	26.76	NA	26.76	663.96
SS003MW110	1-Apr-98	691.58	691.24	19.1	15.0	34.1	30.62	NA	30.62	660.62

TABLE 3.2 (Concluded)
GROUNDWATER ELEVATIONS
SITE S-1 MNATS
KELLY AFB, TEXAS

IRPIMS LOCID	Date	Ground Surface Elevation (ft msl) [a]	TOC Elevation (ft msl)	Screened Interval Top (ft bgs) [b]	Screened Interval Screen Length	Screened Interval Bottom (ft bgs)	Water Level (ft btoc) [c]	Free Product (inches)	Corrected Water Level (ft btoc)	Groundwater Elevation (ft msl)
SS003MW119	1-Apr-98	691.55	691.46	NA	NA	NA	27.33	NA	27.33	664.13
SS003MW120	1-Apr-98	691.00	690.82	NA	NA	NA	24.91	NA	24.91	665.91
SS003MW120	18-Jun-98	691.00	690.82	NA	NA	NA	26.39	NA	26.39	664.43
SS003MW121	1-Apr-98	691.33	691.17	NA	NA	NA	25.25	NA	25.25	665.92
SS003MW272	1-Apr-98	691.85	691.55	20.5	10.0	30.5	26.21	NA	26.21	665.34
SS003MW272	18-Jun-98	691.85	691.55	20.5	10.0	30.5	29.70	12.00	28.84	662.71
SS003MW273	1-Apr-98	691.96	691.39	23.0	10.0	33.0	30.88	NA	30.88	660.51
SS003MW273	18-Jun-98	691.96	691.39	23.0	10.0	33.0	33.25	1.00	33.18	658.21
SS003MW274	1-Apr-98	691.72	691.11	21.0	10.0	31.0	27.70	NA	27.70	663.41
SS003MW274	18-Jun-98	691.72	691.11	21.0	10.0	31.0	26.25	NA	26.25	664.86
SS003MW275	1-Apr-98	690.70	690.37	16.5	10.0	26.5	23.93	NA	23.93	666.44
SS003MW275	19-Jun-98	690.70	690.37	16.5	10.0	26.5	25.36	NA	25.36	665.01
SS003RW111	1-Apr-98	690.34	688.09	18.4	10.0	28.4	24.90	NA	24.90	663.19
SS003RW112	1-Apr-98	690.07	688.00	13.3	15.0	28.3	25.20	NA	25.20	662.80
SS003RW115	1-Apr-98	691.07	688.95	18.0	15.0	33.0	30.82	NA	30.82	658.13
SS003RW116	1-Apr-98	691.07	688.91	18.4	15.0	33.4	26.00	NA	26.00	662.91
SS003RW202	1-Apr-98	691.61	691.03	23.5	10.0	33.5	30.68	NA	30.68	660.35
SS003RW202	18-Jun-98	691.61	691.03	23.5	10.0	33.5	31.98	NA	31.98	659.05
SS050MW156	1-Apr-98	693.02	692.79	NA	NA	NA	30.97	NA	30.97	661.82
SS050MW157	1-Apr-98	692.64	692.32	NA	NA	NA	32.27	NA	32.27	660.05
SS050MW159	1-Apr-98	691.45	691.21	NA	NA	NA	31.41	NA	31.41	659.80

[a] IRPIMS LOCID = Installation Restoration Program Information Management System Location Identification.

[b] ft msl = Feet above mean sea level.

[c] ft bgs = Feet below ground surface.

[d] ft btoc = Feet below top of casing.

[e] Calculated as: [total depth to water -((free-product thickness) * (0.860))], where 0.86 is the specific gravity of product (Section 4.1.1).

[f] NA = Not available or not applicable.

[g] groundwater level abnormally low due to slowly recharging formation.

022/732351/9.xls. Table 3.2

LEGEND

MONITORING WELL LOCATION
"RW" IDENTIFIER INDICATES
A RECOVERY WELL

FENCE

APPROXIMATE LIMIT OF FORMER
TOPOGRAPHIC DEPRESSION AREA

662 — INFERRED LINE OF EQUAL
GROUNDWATER SURFACE ELEVATION IN
FEET ABOVE MEAN SEA LEVEL (MSL)

INFERRED GROUNDWATER
FLOW DIRECTION

FEET

0   100   200   400

FIGURE 3.5

GROUNDWATER ELEVATIONS
APRIL 1998

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado

LEGEND

MONITORING WELL LOCATION
"RW" IDENTIFIER INDICATES
A RECOVERY WELL

FENCE

APPROXIMATE LIMIT OF FORMER
TOPOGRAPHIC DEPRESSION AREA

—659— INFERRED LINE OF EQUAL
GROUNDWATER SURFACE ELEVATION
FEET ABOVE MEAN SEA LEVEL (MSL)

INFERRED GROUNDWATER
FLOW DIRECTION

FIGURE 3.6

GROUNDWATER ELEVATIONS
JUNE 1998

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado

FEET
0   100   200   400

LEGEND

◆ MONITORING WELL LOCATION "RW" IDENTIFIER INDICATES A RECOVERY WELL

—x— FENCE

⬭ APPROXIMATE LIMIT OF FORMER TOPOGRAPHIC DEPRESSION AREA

—680— LINE OF EQUAL GROUNDWATER ELEVATION IN FEET ABOVE MEAN SEA LEVEL (MSL)

⬇ INFERRED GROUNDWATER FLOW DIRECTION

FEET

0   80   160   320

FIGURE 3.7

GROUNDWATER ELEVATIONS
MARCH 1995

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado

S:\ES\ood\733251\KELLY\98dh0684.dwg, 09/14/98 at 11h36

TABLE 3.3
AVERAGE GROUNDWATER EXTRACTION RATES
SITE S-1 MNA TS
KELLY AIR FORCE BASE, TEXAS

Recovery Well	Groundwater Extraction Rate (gpm)
SS003RW111	0.22
SS003RW112	0.08
SS003RW113	0.00
SS003RW114	0.44
SS003RW115	0.01
SS003RW116	0.19

Source: SAIC, 1997. (Measured between April 1996 and November 1997)

Groundwater elevations in the former sump area in 1992 were approximately 4.5 feet higher than any other groundwater elevations recorded at the site (CH2M Hill, 1998). The unusually high groundwater elevations likely were related to increased seasonal rainfall rates over the San Antonio area; there is no record of accidental or intentional water releases at or near the site in 1992. A summary of precipitation rates for the San Antonio area from 1885 to 1997 are provided on Figure 3.8. The five-year moving average shown indicates a cycling of relatively wet to relatively dry periods approximately every 6 to 8 years over the past 2 decades. For instance, the San Antonio area experienced drier seasons during 1988 and 1989, followed by relatively wet seasons from 1990 to 1994. The years 1995 and 1996 had similar precipitation rates as those experienced in 1988 and 1989. It is reasonable to assume that future annual rainfall rates in excess of 40 inches per year would result in similar groundwater highs similar to those observed in 1992.

The slope of the water table closely follows that of the Navarro Formation surface. Prior to pump-and-treat operations, the horizontal hydraulic gradient in the source area was 0.02 foot per foot (ft/ft) (Figure 3.7). This gradient declined to 0.0008 ft/ft as the Navarro surface flattened to the northeast. Three of the six groundwater extraction wells located cross-gradient and downgradient from Site S-1 (SS003RW114 to -RW116) have since created a depression in the water table, resulting in an increase in the hydraulic gradient to 0.03 ft/ft at least 200 feet upgradient from the recovery wells. The groundwater elevation data for May 1997 suggest that horizontal hydraulic gradients in the source area may be as high as 0.05 ft/ft due to the pump-and-treat system (SAIC, 1997).

A consistent horizontal hydraulic gradient of 0.0008 ft/ft has been measured beneath the residential area northeast of Site S-1, regardless of whether or not the pump-and-treat system was operating. The relatively thin saturated zone where the groundwater recovery wells are located minimizes the effective radius of the groundwater pump-and-treat system. Along flowlines peripheral to the groundwater depression (e.g., SS003MW019 to SS003MW001 or SS003RW26 to SS003MW007), horizontal hydraulic gradients are approximately 0.003 ft/ft and decrease to 0.0008 ft/ft in the residential area.

FIGURE 3.8
ANNUAL PRECIPITATION FOR SAN ANTONIO, TEXAS
SITE S-1 MNA TS
KELLY AIR FORCE BASE, TEXAS
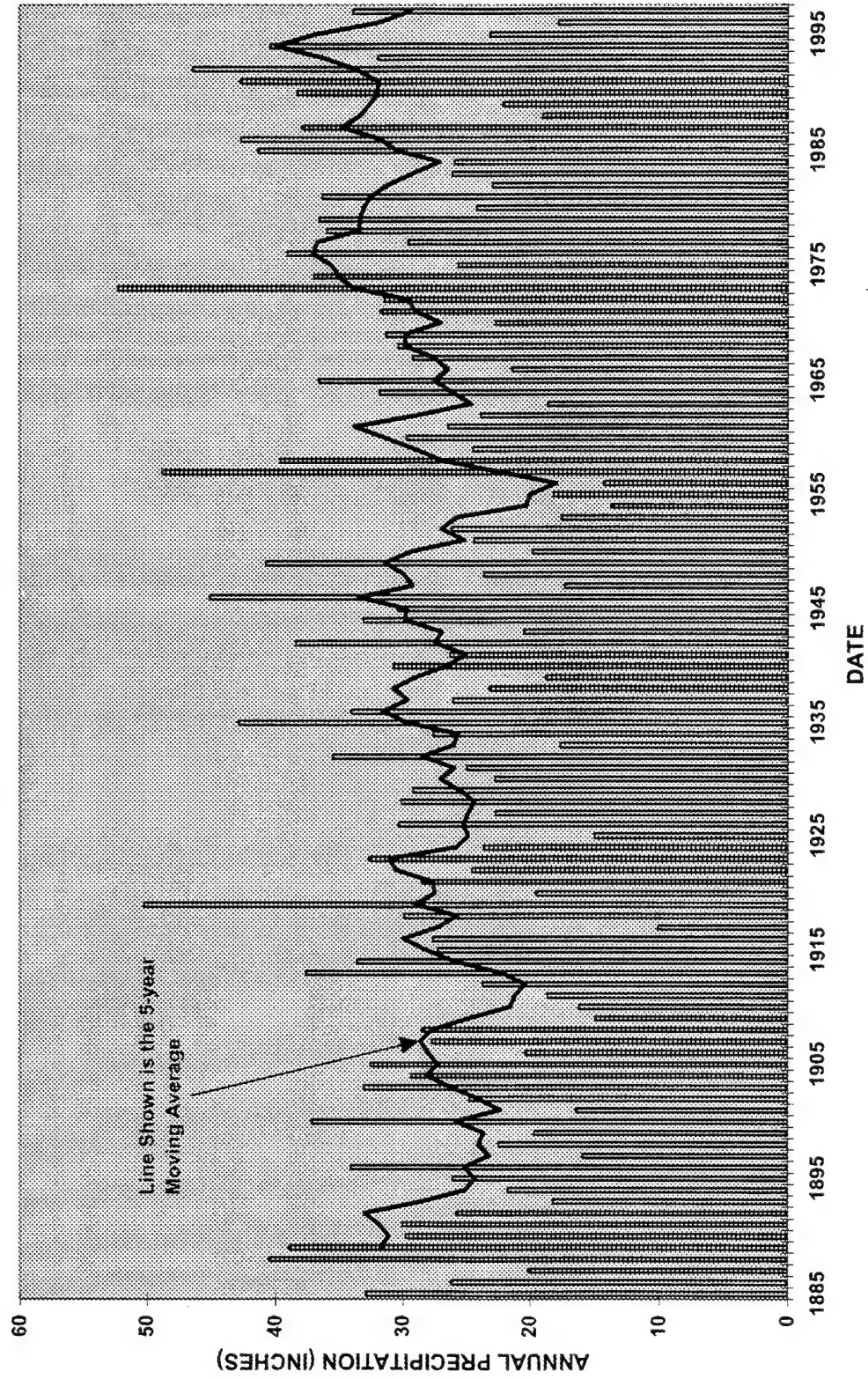
The April 1998 groundwater elevation at SS003MW008 (southeast of the source area) was approximately 7 to 10 feet higher than previously measured between March 1995 and October 1997 (Appendix A). This anomaly suggests that a temporal groundwater mound existed, perhaps due to a surface or subsurface water release. Monitoring well SS003MW008 is located near area P1594 which contains water supply spigots used by military vehicles. However, maintenance personal had not reported water releases or ruptured lines at the site during this period. Alternatively, the anomaly may indicate a measurement error.

The groundwater elevation at monitoring well SS003MW008 was remeasured in June 1998 to reconfirm the presence of a groundwater mound. Eleven additional groundwater elevations also were measured from monitoring wells during the same event (Table 3.2 and Figure 3.6). The groundwater mound was not evident during this event. In general, groundwater elevations in June 1998 were approximately 1 foot lower than in April 1998. However, groundwater gradients in April and June 1998 were very similar. For instance, the June 1998 gradient in the source area was approximately 0.03 ft/ft, decreasing to approximately 0.0007 ft/ft beneath the residential area. A large groundwater depression persisted near recovery wells SS003RW114 and SS003RW115 due to groundwater pump and treat activities.

3.3.1.2 Hydraulic Conductivity

In order to estimate the hydraulic conductivity of the shallow aquifer at Site S-1, slug tests were performed by HNUS at 13 wells in 1989 (HNUS, 1994). Rising and falling head data collected during the test were analyzed using the Bouwer and Rice (1976) method to calculate hydraulic conductivity. The results of these hydraulic conductivity tests are summarized in Table 3.4. Hydraulic conductivities at the site were calculated to range from 7.1×10^{-3} centimeters per second (cm/sec) to 6.7×10^{-1} cm/sec. The approximate hydraulic conductivity in the source area and downgradient from the source area along the path of plume migration is approximately 2.2×10^{-2} cm/sec (average conductivity at monitoring wells SS003MW020, -RW004, -MW019, -MW001, and -MW011). The average hydraulic conductivity from all slug test values was determined to be 9.7×10^{-2} cm/sec.

In addition to slug tests, a 19-hour pumping test was performed at Site S-1 in 1990 (HNUS, 1994). The pumping test was performed at pumping well PW02 and observations wells OW07 to OW11, located approximately 200 feet due north of the aboveground POL tank at the site and just north of the installation boundary of Growdon Drive (see Appendix A). The average transmissivity of the pumping test area was calculated to be 983 square feet per day (ft^2/day). Assuming an average saturated alluvial aquifer thickness of 4 feet, the average hydraulic conductivity across the pumping test area was 8.7×10^{-2} cm/sec, which is similar to the average value derived from slug tests of 9.7×10^{-2} cm/sec.

3.3.1.3 Effective Porosity

Effective porosity is a difficult parameter to quantify and published literature values typically are used to provide effective porosity estimates when other data are unavailable. Effective porosity (or specific yield in the case of an unconfined aquifer with no change in head with depth) can be estimated from pumping tests in cases where

TABLE 3.4
HYDRAULIC CONDUCTIVITY ESTIMATES
SITE S-1 MNA TS
KELLY AFB, TEXAS

Original Well ID	Current Well ID	Hydraulic Conductivity (cm/sec)
QQ	SS003MW019	0.021
RR	SS003MW020	0.007
VV	SS003MW021	0.042
S101	SS003MW001	0.014
S102	SS003MW002	0.025
S103	SS003MW003	0.020
S104	SS003MW004	0.021
S107	SS003MW007	0.154
S108	SS003MW008	0.026
S110	SS003MW010	0.117
S111	SS003MW011	0.047
S113	SS003MW013	0.673
S115	SS003MW015	0.097
	Average	0.097

Source: HNUS, 1994.

multiple observation wells are monitored. Based on the 19-hour pumping test performed in 1990 by Halliburton NUS, the average specific yield of the aquifer was estimated at 0.30 based on values ranging between 0.14 and 0.47. This specific yield is reasonable considering the prevalence of coarse sand to coarse gravel in the shallow aquifer at Site S-1; published specific yields for these soil types range from 0.13 to 0.43 (Anderson and Woessner, 1992). The average effective porosity of 0.3 was assumed to be representative of the shallow aquifer at Site S-1.

3.3.1.4 Advective Groundwater Velocity

The advective velocity of groundwater in the direction parallel to groundwater flow is given by:

$$\bar{v} = \frac{K}{n_e} \frac{dH}{dL}$$

Where: $\bar{v}$ = Average advective groundwater velocity [L/T] (feet per day [ft/day])
  K = Average hydraulic conductivity [L/T] (ft/day)
  dH/dL = Average gradient [L/L] (ft/ft)
  n_e = Effective porosity (0.3).

Highly variable surface profiles of both the Navarro formation and the groundwater table indicate that groundwater velocities should vary considerably. Therefore, groundwater velocities at the site were measured in separate zones. These zones were: zone 1- the source area; zone 2 - downgradient from the source area on the periphery of

the groundwater depression; and, zone 3 - downgradient beneath the residential area (between monitoring wells SS003MW010 and -MW016). Groundwater gradients estimates for zones 1, 2, and 3 were 0.03, 0.003, and 0.0008 ft/ft, respectively. Approximate hydraulic conductivities for these zones based on slug tests (Table 3.4) are 0.016 cm/sec, 0.018 cm/sec, and 0.059 cm/sec, respectively. Using the above relationship in conjunction with estimated gradients and hydraulic conductivities for the zones, the estimated groundwater velocities are 4.59, 0.52, and 0.45 ft/day, respectively. The estimated time required for a particle of water to travel from the former sump area to monitoring well SS003MW016 along flowpaths peripheral to the influence of groundwater pump-and-treat system (or under natural conditions) is 7.5 years based on groundwater flow conditions measured in 1998.

The volumetric flow rate of groundwater between recovery wells SS003RW114 and SS003RW115 was 826 gpd based on the following assumptions: 1) the distance between recovery wells SS003RW114 and SS003RW115 was 150 feet; 2) the groundwater velocity was 4.59 ft/day; 3) the soil porosity was 0.3; and 4) the average aquifer thickness was 4 feet. Therefore, the combined groundwater extraction rate from recovery wells SS003RW114 and SS003RW115 of 648 gpd was equivalent to 78 percent of the groundwater volumetric flow between these recovery wells.

SECTION 4

CONTAMINANT DISTRIBUTION AND EVIDENCE FOR BIODEGRADATION

Soil and groundwater have been contaminated as a result of former solvent disposal activities at Site S-1. Work performed as part of the Phase 1 Interim Measures FFS (HNUS, 1994), the Final Draft FFS Report (CH2M Hill, 1997), the Basewide Operation and Maintenance Site Evaluation Technical Report (SAIC, 1997), and the Draft Site S-1 Soil FFS (CH2M Hill, 1998) attempted to define the nature and extent of contamination. Data collected during those efforts were supplemented with data collected during natural attenuation sampling from April to June 1998 and are presented in the following subsections. In particular, this section focuses on data useful for evaluating and modeling the natural attenuation of chlorinated benzene compounds dissolved in groundwater.

4.1 CONTAMINANT SOURCES AND SOIL QUALITY

The two potential source areas originally identified at the site included the former sump area and the spoils pile area (HNUS, 1994). These potential source areas were identified based on an aerial photograph of the site and interviews with Kelly AFB personnel familiar with the site. It was later determined that the spoils pile area was used to store clean fill and did not contribute to contamination at the site. Contamination of soils was primarily due to the past storage of hazardous wastes, including mixed solvents, carbon cleaning compounds, and POL stored in aboveground tanks. Wastes were stored at Site S-1 from an unconfirmed start date in the 1960s until the cessation of storage activities in 1973 (HNUS, 1991). The waste from the tanks occasionally spilled and flowed into the sump area where the ASTs were located (Figure 1.3). The sump area, ASTs, and the spoils pile were located within a larger depression at the site (Figure 1.3). Contractors collected waste liquids from storage tanks for off-site recovery. The tanks often overflowed during loading and unloading, and additional contamination flowed into the depressed area. A history of the source of the CB and DCB waste streams that were transported to and stored at Site S-1 is unavailable. Turco Carbo Strip and probably other similar formulations were used extensively by large Air Force Bases for removal of carbon from jet engine parts (Spain, 1998). The solvent was composed of o-DCB and 25 percent cresylic acid. It is probable that Kelly AFB used similar solvent formations for their degreasing activities.

A large amount of soil analytical data have been collected through various RI, FFS, and other sampling efforts conducted for Site S-1. The following sections describe soil contaminant trends and primarily are based on historic soil analytical data. Where pertinent, this historic soil data is supplemented by soil analytical information collected as part of this study between March 24 and 28, 1998.

4.1.1 Mobile LNAPL Contamination

During previous investigations, residual and mobile LNAPL within the soil matrix was identified within the clayey, plastic fill material at depths between 18 and 24 feet bgs within the former sump area (CH2M Hill, 1998). The LNAPL was observed as an oily layer or sheen within the clayey material. The CB distribution in the oily LNAPL zones was discontinuous, with high concentrations detected at some locations, and low concentration detected at others. Elevated CB concentrations also were detected in samples with no reported LNAPL (CH2M Hill, 1998).

The presence of the oily layer within the former sump area was reconfirmed during the drilling of monitoring well SS003MW272 as part of this study. A fluidized, oily soil layer was encountered between 23 and 27.5 feet bgs at this location. A soil sample collected at 27 to 27.4 feet bgs indicated CB concentrations of 580 milligrams per kilogram (mg/kg) (Table 4.1). Other chlorinated solvents or fuel constituents were present at concentrations less than 100 mg/kg at this location. A free product layer was not observed on the water table in monitoring well SS003MW272 within 5 days of the installation of the well. The fluidized, oily layer is likely the primary source of groundwater contamination at Site S-1 as it coincides with the location of maximum groundwater CB concentrations (Section 4.5.2).

Previous IRP, RI, and FFS investigation reports reviewed as part of this study did not mention mobile LNAPL on the groundwater surface; however, mobile LNAPL was observed in monitoring well SS003RW114 in March/April 1998. A sample of this LNAPL was collected for laboratory analysis. The LNAPL sample was black in color, mildly aromatic, and had an apparent viscosity similar to a fuel or solvent when shaken. Approximately 8 inches of product were extracted in a bailer during the collection of an LNAPL sample. The analytical results for product samples collected at SS003RW114 are shown in Table 4.2.

During a supplementary groundwater sampling event in June 1998, mobile LNAPL was observed in monitoring wells SS003MW053, SS003MW120, SS003MW272, and SS003MW273. Groundwater elevations at these locations generally were 1 foot lower than measured in March/April 1998 which resulted in gravitational draining of LNAPL formerly trapped in saturated soils. Free product was observed as a thick sheen in monitoring well SS003MW053. Monitoring well SS003MW120 contained 0.3 inch of product, and wells SS003MW272 and -273 contained approximately 1 foot and 1 inch of product, respectively. Water was not observed within well SS003MW272 below the product layer. A sample of free-product was collected from monitoring well SS003MW272, and the results are summarized in Table 4.2.

The VOCs measured in both LNAPL samples collected at the site (Table 4.2) are primarily CB and DCB compounds with smaller fractions of fuel hydrocarbons. CB and DCB compose approximately 68 percent of the VOCs and SVOCs by weight detected in sample SS003RW114. Approximately 92 percent of the measured VOCs and SVOCs by weight at SS003MW272 consisted of CB and DCB. Monitoring well SS003RW114 is located beyond the former sump area in a downgradient location. Reduced CB and DCB concentrations in LNAPL at this well suggest that this product may have originated in the former sump area and has weathered during migration from the sump area to SS003RW114. This observation is supported by the presence of a

TABLE 4.1
CONTAMINANTS DETECTED IN SOIL
SITE S-1 MNA TS
KELLY AIR FORCE BASE, TEXAS

Sample ID	Depth (ft bgs)[b]	1,2-DCB[a] (mg/kg)[c]	1,3-DCB (mg/kg)	1,4-DCB (mg/kg)	cis-1,2-DCE (mg/kg)	Methylene Chloride (mg/kg)	Naphthalene (mg/kg)	TeCE[a] (mg/kg)	TCE[a] (mg/kg)	Benzene (mg/kg)	Chlorobenzene (mg/kg)	Toluene (mg/kg)	TPH[a] (mg/kg)
SS003MW272	16 16.5	.25 U[d]	.18	2.2	.75 U	.15	1	.88 U	1.2 U	.25 U	3.4	.62 U	NA[e]
SS003MW272	27 27.4	99	5.9	80	38 U	6.7	22	44 U	60 U	3.8	580	31 U	NA
SS003MW273	16 16.5	.01 U	.03 U	.014	.03 U	.025 U	.013	.035 U	.05 U	.01 U	.17	.025 U	NA
SS003MW273	30 31	.25 U	.2	1.7	.75 U	.16	2	.88 U	1.2 U	.25 U	1.6	.62 U	NA
SS003MW274	15 16	.002 U	.006 U	.002 U	.006 U	.005 U	.007 U	.007 U	.01 U	.002 U	.015	.005 U	NA
SS003MW274	30 31	1.1	.13	.45	.75 U	.13	.72	.88 U	1.2 U	.25 U	5.6	.62 U	NA
SS003MW275	16.5 17	.002 U	.006 U	.002 U	.006 U	.005 U	.007 U	.007 U	.01 U	.002 U	.002 U	.005 U	NA
SS003SB277	30 33	.098	.75 U	.27	.75 U	.13	.9	.88 U	1.2 U	.25 U	6.8	.62 U	NA
SS003SB278	29 30	.002 U	.006 U	.002 U	.006 U	.005 U	.007 U	.007 U	.01 U	.002 U	.002 U	.005 U	NA

[a] DCB = Dichlorobenzene
DCE = Dichloroethene
TCE = Trichloroethene
TeCE = Tetrachloroethene
TPH = Total Petroleum Hydrocarbons

[b] ft bgs = Feet below ground surface.

[c] mg/kg = milligrams per kilogram.

[d] U = The analyte was analyzed for and is not present above the associated reporting limit.

[e] NA = Not analyzed.

Note: All samples were analyzed in accordance with Test Methods for Evaluating Solid Wastes, SW-846, Third Edition (USEPA, 1996b) or Methods for Chemical Analysis of Water and Wastes, Third Edition (USEPA, 1983).

contaminant smear zone leading from the source area to the northeast in the direction of groundwater flow (see Section 4.1.2). The presence of chlorobenzenes and fuel hydrocarbons in both LNAPL samples is consistent with the knowledge that chlorobenzenes were commonly-used degreasing compounds.

TABLE 4.2
ANALYSES OF LNAPL OBSERVED IN MONITORING
WELLS SS003RW114 AND SS003MW272
SITE S-1 MNA TS
KELLY AIR FORCE BASE, TEXAS

Analyte	Analytes Detected at SS003RW114 (mg/kg)[a]	Analytes Detected at SS003MW272 (mg/kg)
Volatile Compounds:		
1,2,4-Trichlorobenzene	110	710
1,2,4-Trimethylbenzene	81	530J
1,2-Dichlorobenzene	4,100	55,000
1,3-Dichlorobenzene	300	4,000
1,4-Dichlorobenzene	1,500	14,000
Benzene	220	<620
Toluene	<400	430
m- and p-Xylene	<250	370
Chlorobenzene	7,400	20,000
Semi-Volatile Compounds:		
Di-n-butyl phthalate	310	<5,000
bis(2-Ethylhexyl)phthalate	4,200	2,500
Fluoranthene	120	ND
2-Methylnaphthalene	770	1,400
Naphthalene	310	1,200
TPH[b]	1,080	1,180,000
Density	0.859 grams per cubic centimeter	0.885 grams per cubic centimeter

[a] mg/kg=Milligrams per kilogram.

[b] TPH = total petroleum hydrocarbons.

4.1.2 Soil Contamination

During RI activities for Site S-1 performed in the early 1990s, 88 soil samples were collected within the former sump area during monitoring well installation (HNUS, 1994; CH2M Hill, 1998). Soil analytical results indicated significant soil contamination throughout the sump area, primarily in the form of CB, 1,4-DCB, 1,2-DCB, 1,3-DCB, and 1,2,4-TCB. The maximum CB concentration was 1,200 mg/kg at S1-B11, located not more than 25 feet southeast of monitoring well SS002MW272 (Figure 2.1; S1-B11 not shown on figure). Appendix A contains information related to this study. Other contaminants such as benzene, tetrachloroethene (PCE), trichloroethene (TCE), total dichloroethene (DCE), and vinyl chloride were detected at S1-B11 at concentrations less than 0.14 mg/kg. In general, it was determined that VOC concentrations were highest

below 12 feet bgs and extended to the water table along the entire length of the sump, but diminished in the vadose zone with distance from the former sump area.

Additional soil sampling at Site S-1 was performed in 1997 as part of the Basewide Operation and Maintenance program for IRP Zone 5 (SAIC, 1997). These new soil borings were identified as SS003SB197 through -201 and SS003SB205 (aka SB197 through SB201, and SB205). Soil boring SS003SB199 was drilled at the suspected source "hot spot," while the remaining borings were drilled along the suspected perimeter of the source area (Figures 4.1 and 4.2). Ten additional soil borings were drilled by CH2M Hill (1998) in 1997 to further delineate the extent of contamination. These soil borings included soil borings SS003SB208 through SS003SB217 (aka SB208 through SB217). CH2M Hill (1998) compiled all available historic soil sampling results along with their new soil boring data to create the most complete available contaminant profile summary for Site S-1. These contaminant profile summaries for CB contamination in the 2- to 20-foot-bgs and greater than 20-foot-bgs intervals are shown on Figures 4.1 and 4.2.

Residual LNAPL contamination is present as a smear zone approximately 7- to 10-feet thick, located above and below the water table. The pattern of residual LNAPL contamination indicates the former downgradient spreading of mobile LNAPL from the sump area to 250 feet to the northeast, in the direction of groundwater flow. The migration of LNAPL contamination from the sump area is evident from the presence of free-product contamination observed at SS0003RW114 and SS003MW273. CB concentrations in soil at depths between 2 and 20 feet bgs ranged from not detected (ND) to 190 mg/kg at SS03SB210 (Figure 4.1). Soil boring SB210 is located near the mid-point of the former sump. The greatest concentrations of CB were found at depths below 12 to 14 feet bgs, which may correspond to the original depth of the sump prior to its closure and backfilling it with soil. Near the bottom of the vadose zone (>20 feet bgs), CB concentrations increased in lateral extent. This increase in CB extent supports the past migration of LNAPL on top of the water table and subsequent sorption to soil particles. A CB concentration of 29 mg/kg was detected at SB198, approximately 300 feet downgradient from the sump. The maximum detected CB concentration near the bottom of the vadose zone was 88 mg/kg at soil boring SB212 between 24 and 26 feet bgs (Figure 4.2).

Other contaminants detected in soils in 1997 included 1,2-DCB, 1,4-DCB, 2-methylnapthalene; naphthalene; benzene, toluene, ethylbenzene, and xylenes (BTEX); and TPH (CH2M Hill, 1998). Minor traces of 1,2,3-TCB (maximum of 5.2 mg/kg), 1,2,4-TCB (maximum of 10.5 mg/kg), and TCE (maximum of 1 mg/kg) also were detected during site characterization activities conducted by SAIC (1997). TPH concentrations ranged from 9.7 to 32,700 mg/kg in soil samples collected by CH2M Hill (1998), but TPH concentrations were not always coincident with CB contamination. Interestingly, 1,2-DCB, 1,3-DCB, and 1,4-DCB were measured at 1,790, 61, and 237 mg/kg, respectively, at SS003SB199, and may indicate a localized pocket of DCB contamination. Oxygen concentrations from soil porespace measurements are not available, but the presence of high TPH concentrations suggests that the soil gas likely is oxygen-depleted as a result of aerobic degradation of fuel constituents. If so, it is possible that some DCB sorbed to soil or dissolved in soil moisture in the vadose zone has been anaerobically transformed to CB through the
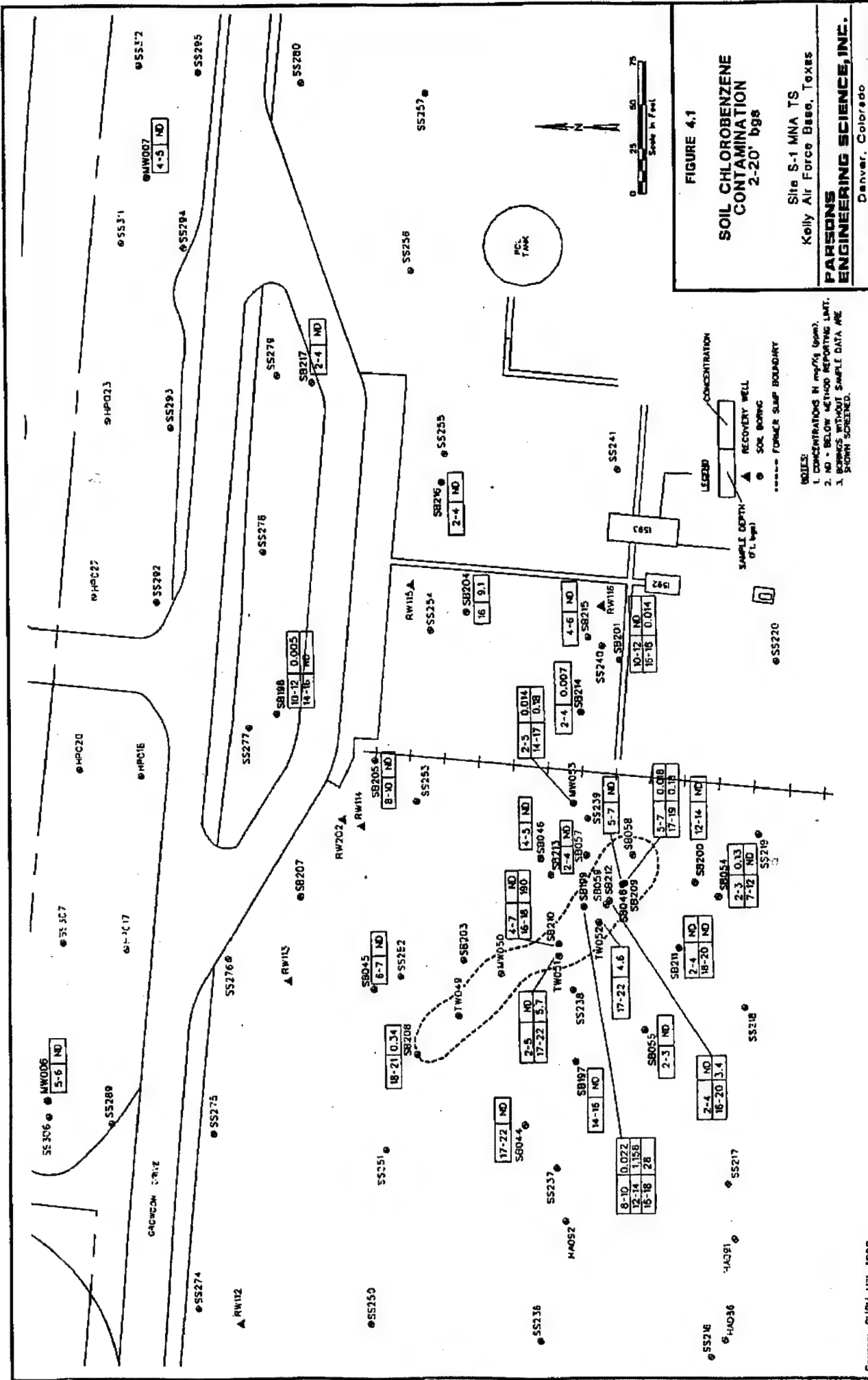
FIGURE 4.1

SOIL CHLOROBENZENE
CONTAMINATION
2-20' bgs

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado

LEGEND

▲ RECOVERY WELL
● SOIL BORING
— — — FORMER SUMP BOUNDARY

CONCENTRATION
SAMPLE DEPTH (FT bgs)

NOTES:
1. CONCENTRATIONS IN mg/Kg (ppm).
2. ND = BELOW METHOD REPORTING LIMIT.
3. BORINGS WITHOUT SAMPLE DATA ARE
   SHOWN SCREENED.

Scale in Feet
0   25   50   75

Source: CH2M Hill, 1998.

K.1/25231\KELL\ON0275\ 03/13/98 at 3:09

FIGURE 4.2

SOIL CHLOROBENZENE
CONTAMINATION
>20' bgs

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado

Source: CH2M Hill, 1998.
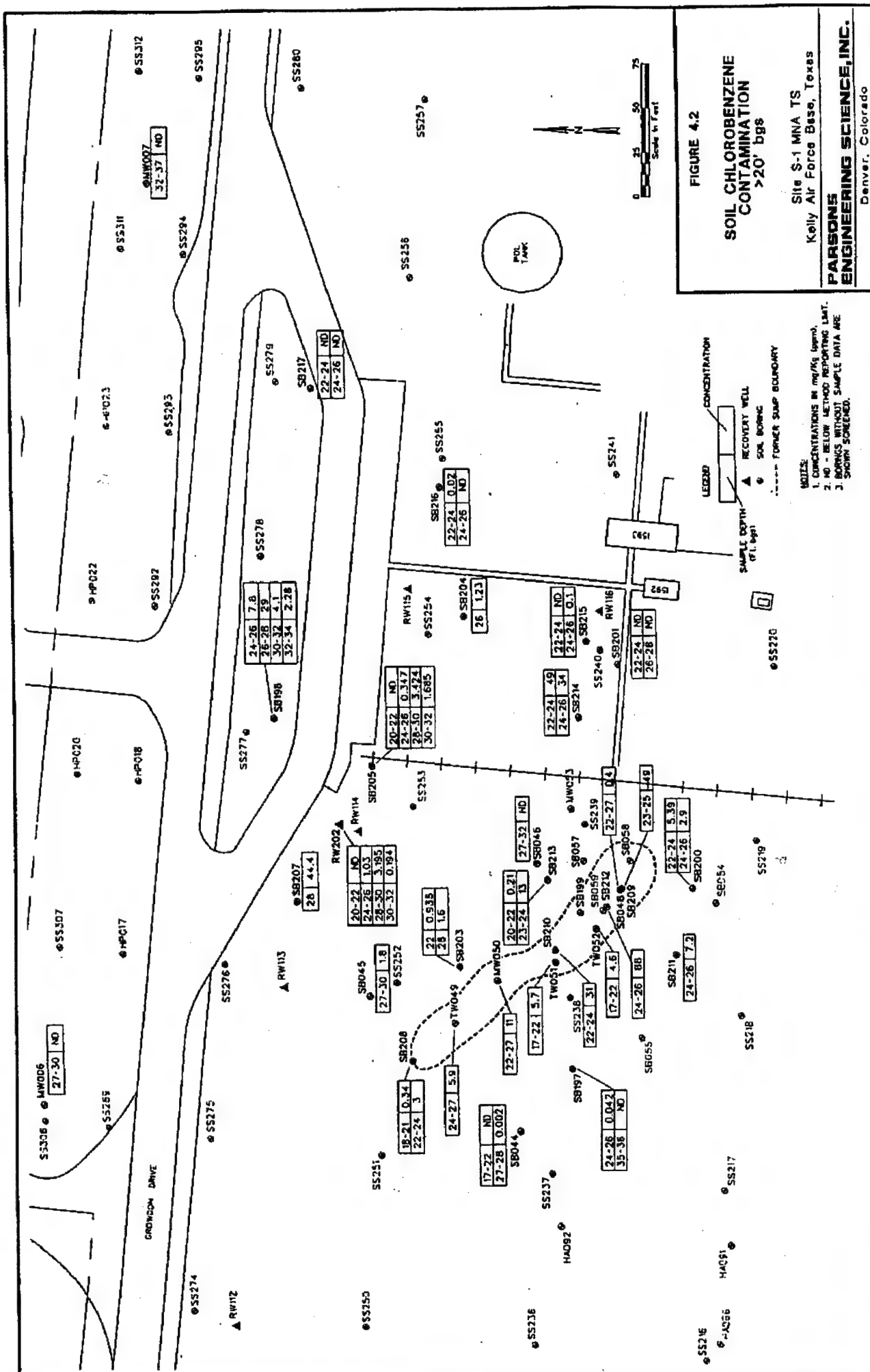
process of reductive dechlorination, a process which occurs in anaerobic groundwater environments (e.g., Bosma *et al.*, 1988, Fathepure *et al.*, 1988; Fathepure and Vogel, 1991; Holliger *et al.*, 1992; Ramanand et al., 1993).

Soil data collected as part of this study provide little additional delineation of source area contamination; however, the data do confirm previous observations of soil contamination. Low concentrations of chlorobenzenes were detected at most soil sampling locations in this study because they were located primarily north/northeast of the former sump (SS003MW273 and SS003MW274), which is consistent with previous observations (CH2M Hill, 1998). No contamination was detected at the soil boring for SS003MW275, which is located upgradient from the source area.

A soil gas survey was conducted by SAIC (1998) in February 1998 to further delineate contaminant "hot spots" identified during soil sampling performed for the Basewide Operation and Maintenance Site Evaluation. Preliminary soil gas survey results are summarized in Figures 4.3 to 4.5. Soil gas data indicate that volatile organic compound (VOC) contamination is present at concentrations above 10 micrograms per liter (µg/L) in the vicinity of and downgradient from the sump area. The most widespread detection of soil gas VOCs occurred at a depth interval of approximately 18 feet bgs. This interval coincides with the presence of a clay zone where significant soil contamination is sorbed. Fewer soil gas samples were collected near the groundwater table at 21 to 24 feet bgs, but contamination at this depth also is widespread and likely represents the presence of mobile and residual LNAPL in the gravelly layer atop the Navarro formation. Soil gas results confirm the spreading of LNAPL from the sump area to the northeast. A trend that is apparent in the soil gas results, but less apparent in soil analytical results (Figures 4.4 and 4.5) is the presence of VOCs southeast of the former sump area.

To date, significant measures have not been undertaken to remediate soil contamination. RFH soil decontamination testing was performed at Site S-1 between 1993 and 1994 (HNUS, 1995). RFH soil decontamination is a heat-assisted SVE process for SVOCs that was being evaluated by the Air Force Materiel Command (AFMC) and the Air Force Center For Environmental Excellence (AFCEE). Two RFH decontamination processes developed by IIT Research Institute (using ground and exciter electrodes) and KAI Technologies, Inc. (using an antenna-like device) were tested to determine if soils could be heated and vapors removed. The testing was performed near the former sump area and near the perimeter fence (in the approximate vicinity of monitoring well SS003MW050). Approximately 2,000 square feet of test area were treated from ground surface to the top of the water table. Numerous soil samples were collected in the treatment areas, but analytical results were not formally reported because of suspicions about matrix interference and contaminant detections in trip blanks. Treatment efficiency and VOC soil concentrations remaining at the study locations remain in question.

LEGEND

■ Soil Gas Sampling Point With
   Chlorobenzene Concentration

⌒10⌒ Line of Equal Soil Gas
   Chlorobenzene Concentration (μg/L).
   Dashed Where Inferred

——— Fence

N

0 25 50
   Feet

Data Source: SAIC, 1998.

FIGURE 4.3

CHLOROBENZENE
SOIL GAS RESULTS
AT 12 FEET BGS
(FEBRUARY 1998)

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado

LEGEND

■ Soil Gas Sampling Point With
  Chlorobenzene Concentration

╱10╱ Line of Equal Soil Gas
  Chlorobenzene Concentration (µg/L),
  Dashed Where Inferred

──×── Fence

N

0   25   50
     Feet

Data Source: SAIC, 1998.

FIGURE 4.4

CHLOROBENZENE
SOIL GAS RESULTS
18 FEET BGS
(FEBRUARY 1998)

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado

LEGEND

■ Soil Gas Sampling Point With Chlorobenzene Concentration

⌒10⌒ Line of Equal Soil Gas Chlorobenzene Concentration (µg/L). Dashed Where Inferred

Fence

P1592

Data Source: SAIC, 1998.

FIGURE 4.5

CHLOROBENZENE
SOIL GAS RESULTS
21 - 24 FEET BGS
(FEBRUARY 1998)

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado

0   25   50

Feet

N

4-11

4.2 INDUSTRIAL USES AND PROPERTIES OF CHLORINATED BENZENE COMPOUNDS

4.2.1 Industrial Uses of Chlorinated Benzene Compounds

CB compounds have many industrial and agricultural applications which make them widely used and economically important. CB primarily is used as a solvent in pesticide formulations and in degreasing and other industrial applications (Montgomery, 1996). It is possible that monochlorobenzene was used at Kelly AFB as a metal degreaser or similarly used solvent because oily LNAPL layers at the site commonly had high concentrations of CB. As previously mentioned in Section 4.1, Turco Carbo Strip was used for the removal of carbon from jet engine parts and largely was composed of o-DCB. Similarly, 1,2-, 1,3-, and 1,4-DCB also are widely used as solvents and in manufacturing processes and were also detected in soils at Site S-1. Generally, manufactured 1,3- and 1,4-DCB are used for fumigants or sulfide resin production (1,4-DCB) (Montgomery, 1996).

The compound 1,2,4-TCB was detected in soils and LNAPL at Site S-1, possibly due to its use in dielectric fluids or degreasing operations. 1,2,4-TCB has other uses as a dye carrier and as an intermediate in the manufacture of herbicides and higher chlorinated benzenes, dielectric fluids, solvents, and heat-transfer mediums. Other industrial applications of 1,2,4-TCB included its use in plumbing cleaners, wood preservatives and abrasive formulations. The compound 1,2,3-TCB historically has been detected at lower concentrations than 1,2,4-TCB and was probably used for similar purposes as 1,2,4-TCB; however 1,2,3-TCB is also used for termite control applications and as a chemical intermediate. 1,3,5-TCB primarily is used for organic synthesis, but was not reported at detectable levels at Site S-1.

The heavier chlorinated benzenes such as 1,2,3,4-tetrachlorobenzene (1,2,3,4-TeCB), 1,2,3,5-tetrachlorobenzene (1,2,3,5-TeCB), and 1,2,4,5-tetrachlorobenzene (1,2,4,5-TeCB) are used as chemical intermediates, dielectrics, insecticides, or electrical insulation. Pentachlorobenzene is used in chemical research and the synthesis of other chemicals. Hexachlorobenzene is used for the manufacture of pentachlorophenol, seed fungicides, and wood preservatives. Pentachlorobenzene, hexachlorobenzene, and TeCB have not been detected at Site S-1.

4.2.2 Physical and Chemical Properties of Chlorobenzenes

It is important to understand the physical and chemical properties of chlorinated benzenes in order to determine likely migration patterns and characteristics when released to groundwater. Chlorinated benzenes present as mobile or sorbed LNAPL are primarily subject to natural dissolution, advection, sorption, and volatilization. CB has the highest reported water solubility of the chlorinated benzene compounds and the lowest soil sorption coefficient. Therefore, CB will migrate within a groundwater aquifer faster than other chlorinated benzenes. Water solubility and vapor pressures decrease with increasing chlorination, whereas sorption increases. As a result, TCB and DCB will sorb more strongly to soils, generally be present at lower concentrations in groundwater, and may accumulate more in aquifers with appreciable levels of soil organic carbon. Important physical and chemical parameters of the entire group of chlorobenzenes are shown in Table 4.3.

TABLE 4.3
PHYSICAL AND CHEMICAL PROPERTIES OF CHLOROBENZENES
SITE S-1 MNA TS
KELLY AFB, TEXAS

Compound	Molecular Weight	Reported Solubility (mg/L) at 25°C	Reported Vapor Pressure (mm HG at 25°C)	Reported Henry's Constant (atm-m³/mole) at 25°C	Reported Soil Sorption Coefficient, Log Koc	Reported Octanol/water partition Coefficient, Log Kow
CB	112.56	471.7 to 534	11.9	3.6×10^{-3} to 4.45×10^{-3}	1.92 to 2.5	2.65 to 2.98
1,2-DCB	147	92.7 to 156	1.28 to 1.5	1.57×10^{-3} to 2.4×10^{-3}	2.26 to 3.1	3.34 to 3.55
1,3-DCB	147	133 to 143	1.9 to 2.3	2.63×10^{-3} to 4.7×10^{-3}	2.23	3.38 to 3.72
1,4-DCB	147	65.3 to 90.6	0.4 to 0.7	2.7×10^{-3} to 4.45×10^{-3}	2.2 to 2.93	3.36 to 3.62
1,2,4-TCB	181.45	31.3 to 48.8	0.29 to 0.4	1.42×10^{-3} to 19.2×10^{-3}	2.94 to 5.11	3.63 to 4.23
1,2,3-TCB	181.45	18	2.1	7.1×10^{-4} at 20C	3.24 to 5.09	4.04 to 4.14
1,2,3,4-TeCB	215.89	5.92	2.6 to 3.0	7.00×10^{-3} at 24.2C	3.47 to 5.4	4.37 to 4.94
1,2,4,5-TeCB	215.89	0.465	5×10^{-3}	1.0×10^{-2} at 20C	2.79 to 6.1	4.51 to 4.7
Pentachlorobenzene	250.34	2.24 to 5.37 umol/L	0.006 (at 20 to 30C)	6.58×10^{-4} at 24.2	4.36 to 6.3	4.88 to 5.75
Hexachlorobenzene	284.78	4.7 μg/L at 25	18×10^{-6} mm	1.31×10^{-3} to 1.7×10^{-3}	2.56 to 6.4	3.93 to 5.79

Note: All values referenced from Montgomery (1996).

4.3 OVERVIEW OF CHLOROBENZENE BIODEGRADATION

Mechanisms for natural attenuation of chlorinated benzenes are similar to established processes affecting other chlorinated solvents and BTEX and include: biodegradation, dispersion, dilution from recharge, sorption, and volatilization. Of these processes, biodegradation is the only mechanism working to transform contaminants into ultimately innocuous byproducts. Intrinsic bioremediation occurs when indigenous microorganisms work to bring about a reduction in the total mass of contamination in the subsurface without the addition of nutrients. In order to provide a foundation for interpreting site data, the following subsections review the major bioremediation processes that act upon chlorinated benzenes, chlorinated ethenes, and BTEX compounds.

4.3.1 Review of Biodegradation Processes

Microorganisms obtain energy for cell production and maintenance by facilitating thermodynamically advantageous reduction/oxidation (redox) reactions involving the transfer of electrons from electron donors to available electron acceptors. This results in the oxidation of the electron donor and the reduction of the electron acceptor. Electron donors may be natural organic carbon, fuel hydrocarbon compounds, and chlorinated solvents (e.g., chlorinated benzenes ranging from CB to TeCB). Fuel hydrocarbons or solvents are completely degraded or detoxified if they are utilized as the primary electron donor (i.e., as a primary substrate or carbon source) for microbial metabolism (Bouwer, 1992). Electron acceptors are elements or compounds that occur in relatively oxidized states, and include oxygen, nitrate, ferric iron, sulfate, manganese, carbon dioxide, and chlorinated solvents.

The driving force of biodegradation is electron transfer, which is quantified by the Gibbs free energy of the reaction ($\Delta G°_r$) (Stumm and Morgan, 1981; Bouwer, 1994; Godsey, 1994). The value of $\Delta G°_r$ represents the quantity of free energy consumed ($\Delta G°_r > 0$) or yielded ($\Delta G°_r < 0$) to the system during the reaction. Although thermodynamically favorable, most of the reactions involved in biodegradation of fuel or chlorinated hydrocarbons cannot proceed abiotically because of the lack of activation energy. Microorganisms are capable of providing the necessary activation energy; however, they will facilitate only those redox reactions that have a net yield of energy (i.e. $\Delta G°_r < 0$). Most reactions involving biodegradation of contaminants do yield energy to the microbes; however, in many cases specific geochemical conditions are necessary for this reaction to be favorable and to allow the appropriate microbial population to develop and grow.

Microorganisms preferentially utilize electron acceptors while metabolizing hydrocarbons (Bouwer, 1992). Dissolved oxygen (DO) is utilized first as the prime electron acceptor. It is under these conditions (i.e., aerobic conditions) that fuel hydrocarbons and the less chlorinated solvents are most commonly used as electron donors. After the DO is consumed, anaerobic microorganisms use native electron acceptors in the following order of preference: nitrate, manganese, ferric iron hydroxide, sulfate, and finally carbon dioxide. Under anaerobic conditions, BTEX compounds and other fuel hydrocarbons are still used as electron donors. Chlorinated solvents (including dichlorobenzenes and higher) that are susceptible to reductive dehalogenation generally are used as electron acceptors the more reducing the aquifer becomes (e.g., sulfate reducing or methanogenic conditions).

In addition to being controlled by the energy yield of the reaction, the expected sequence of redox processes also is a function of the oxidation/reduction potential (ORP) of the groundwater. This potential is a measure of the relative tendency of a solution or chemical reaction to accept or transfer electrons. As each subsequent electron acceptor is utilized, the groundwater becomes more reducing, and the ORP of the water decreases. The main force driving this change in ORP is microbially mediated redox reactions. Environmental conditions and microbial competition ultimately determine which processes will dominate.

Depending on the types and concentrations of electron acceptors present (e.g., nitrate, sulfate, carbon dioxide), pH conditions, and ORP, anaerobic biodegradation can occur by denitrification, manganese reduction, ferric iron reduction, sulfate reduction, or methanogenesis. Other, less common anaerobic degradation mechanisms such as manganese or nitrate reduction may dominate if the physical and chemical conditions in the subsurface favor use of these electron acceptors. Vroblesky and Chapelle (1994) show that the dominant terminal electron accepting process can vary both temporally and spatially in an aquifer with fuel hydrocarbon contamination.

4.3.2 Aerobic Biodegradation of Chlorobenzenes

CB and polychlorinated benzenes up to and including TeCB have been shown to be biodegradable under aerobic conditions. Several studies have shown that bacteria are able to utilize CB (Reineke and Knackmuss, 1984), 1,4-DCB (Reineke and Knackmuss, 1984; Schraa et al., 1986; Spain and Nishino, 1987) 1,3-DCB (de Bont et al., 1986), 1,2-DCB (Haigler et al., 1988), 1,2,4-TCB (van der Meer et al., 1987; Sander et al., 1991) and 1,2,4,5-TeCB (Sander et al., 1991) as primary growth substrates in aerobic systems. Nishino et al. (1994) note that aerobic bacteria able to grow on CB have been detected at a variety of chlorobenzene contaminated sites, but not at uncontaminated sites. Spain (1996) notes that this provides strong evidence that the bacteria are selected for their ability to derive carbon and energy from in situ CB degradation.

The pathways for CB and polychlorinated benzene reactions are similar, and are also similar to that of benzene (Chapelle, 1993; Spain, 1996). Figure 4.6 illustrates the initial breakdown of CB and benzene via aerobic biodegradation. The only significant difference between benzene and CB degradation is the elimination of chlorine from CB at some point in the pathway (Chapelle, 1993). Ring cleavage of the catechol intermediate (resulting from benzene degradation) is performed by an ortho or meta cleavage pathway. The ortho pathway results in the cleavage of the catechol ring between the carbon atoms that are carrying the hydroxyl groups, thereby forming cis/cis-muconate. This compound is further oxidized to beta-ketoadipic acid. The meta cleavage pathway is initiated between two carbon atoms, of which only one carries a hydroxyl group. The resulting organic acids are further degraded to carbon dioxide and water. Ring cleavage in 3-chlorocatechol (resulting from CB degradation) is highly specific and results by a modified ortho cleavage pathway described by Evans et al. (1971) and Dorn and Knackmuss (1978) in which a 1,2-dioxygenase catalyzes ring-fission to form 2-chloromuconic acid. The resulting organic acids are further degraded to hydrochloric acid, carbon dioxide, and water.

Benzene

Chlorobenzene

Benzene Dihydrodiol

Chlorobenzene Dihydrodiol

Catechol

3 - Chlorocatechol

Muconic Acid

2 - Chloromuconic Acid

$Cl^{\ominus}$

4 - Carboxymethylenebutenolide

Maleylacetic Acid

β - Ketoadipic Acid

Continued Breakdown to
Co_2 + H_2O
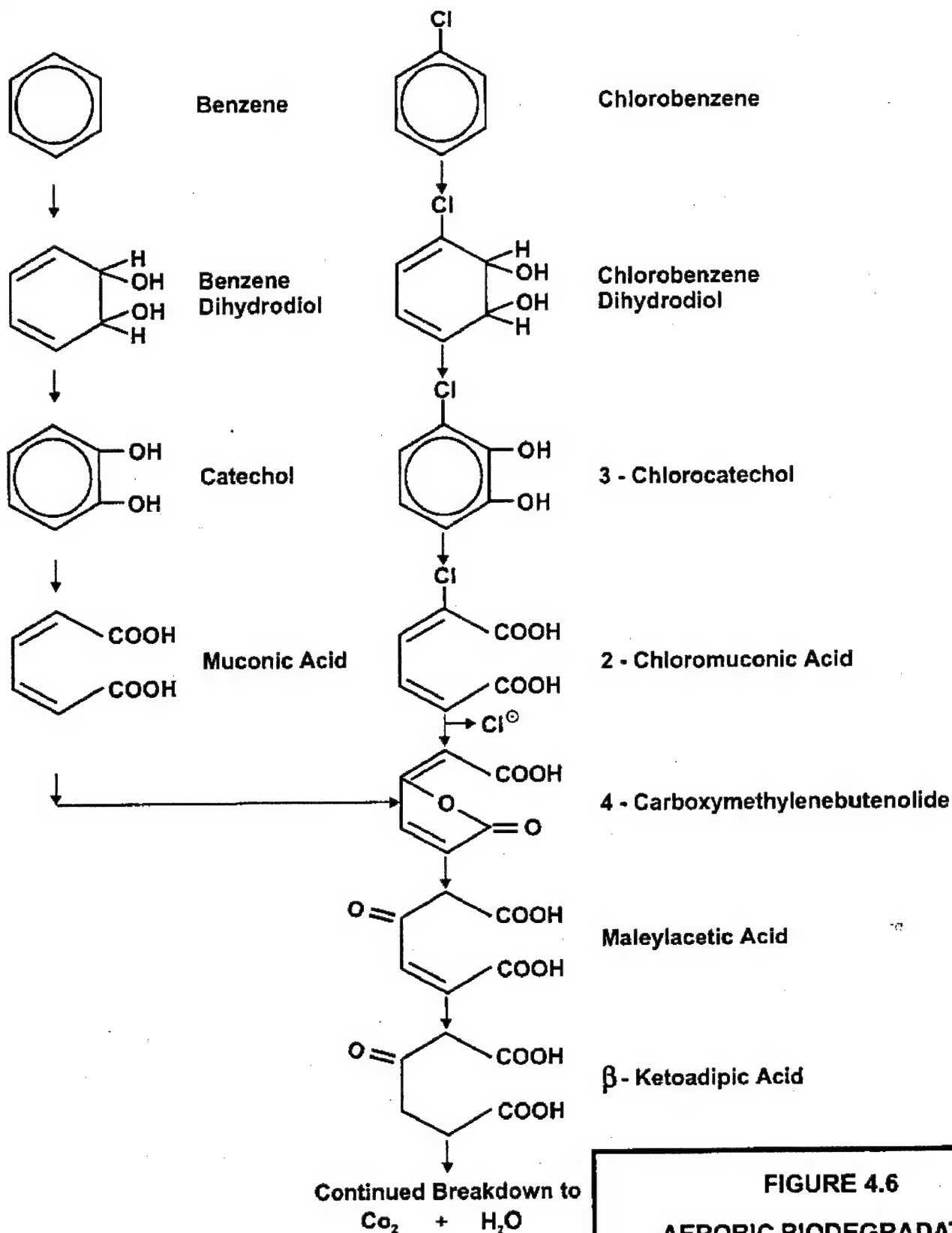
FIGURE 4.6

**AEROBIC BIODEGRADATION
OF CHLOROBENZENE AND
BENZENE THROUGH OR THO
PATHWAY OXIDATION**

Site S-1 RNA TS
Kelly Air Force Base, TX

**PARSONS
ENGINEERING SCIENCE, INC.**

Denver, Colorado

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Similar to CB, DCB isomers are degraded by the initial formation of dihydrodiols, and then by formation of a chlorocatechol (Haigler *et al*, 1988; de Bont *et al*., 1986; Spain, 1990; Spain and Nishino, 1987). The difference in initial dioxygenase attack of the DCB compounds depends on the positions of the chlorine atom on the benzene structure. In general, the ring is initially oxidized at the first two available ring locations adjacent to a chlorine atom to form chlorinated dihydrodiols. The dihydrodiols are then dehydrogenated to yield chlorocatechols, which serve as substrates for ring fission enzymes and subsequent reactions that result in the eventual elimination of the chloride through the modified *ortho* pathway (Evans et al., 1971; Dorn et al., 1974). Therefore, initial degradation of 1,2- (*ortho*), 1,3- *(meta)*, and *1,4- (para)* DCBs will result in the formation of 3,4-dichlorocatechol, 3,5-dichlorocatechol, and 3,6-dichlorocatechol, respectively.

Work on *Pseudomonas* strains (Sander *et al*., 1991) has demonstrated that biodegradation mechanisms used in aerobic CB degradation also are involved in the degradation of TCBs and TeCBs. The compounds 1,2,4-TCB and 1,2,4,5-TeCB proceed through generally the same sequence of CB aerobic oxidation as is depicted in Figure 4.6. The first steps of degradation proceed via the dioxygenation of the benzene nuclei, followed by the formation of 3,4,6-trichlorocatechol. The compounds are then oxidized by *ortho* cleavage to form 2,3,5-trichloromuconate, which is then channeled into a tricarboxylic acid pathway and successive biodegradation to carbon dioxide, water, and hydrochloric acid.

4.3.3 Anaerobic Biodegradation of Chlorobenzenes

For the highly chlorinated benzenes (e.g., hexachlorobenzene and pentachlorobenzene, as well as TeCB, and TCB), reductive dechlorination is the most likely biodegradation mechanism (Holliger *et al*., 1992; Ramanand *et al*., 1993; Suflita and Townsend, 1995). As discussed by Suflita and Townsend (1995), reductive dehalogenation of aromatic compounds has been observed in a variety of anaerobic habitats, including aquifer materials, marine and freshwater sediments, sewage sludges, and soil samples; however, isolation of specific microbes capable of these reactions has been difficult. As with the chlorinated ethenes and ethanes, the chlorinated benzenes are most likely acting as electron acceptors as other sources of carbon and energy are being utilized by microbes or microbial consortia (Suflita and Townsend, 1995).

The actual mechanisms of reductive dehalogenation are not well understood. Furthermore, reductive dehalogenation of chlorinated benzenes has not been as well documented as for other chlorinated solvents. However, reductive dechlorination of chlorinated benzenes has been documented (e.g., Bosma *et al*., 1988, Fathepure *et al*., 1988; Fathepure and Vogel, 1991; Holliger *et al*., 1992; Ramanand *et al*., 1993). As with other chlorinated solvents, the reductive dehalogenation of chlorinated benzenes is affected by the degree of chlorination of the compound. The more chlorinated aromatic compounds are typically more amenable to this reaction (Sulfita and Townsend, 1995; Adriaens and Vogel, 1995). As these compounds are dechlorinated, the daughter products will become more resistant to further reductive dechlorination (Fathepure *et al*., 1988; Bosma *et al*., 1988; Holliger *et al*., 1992). The reductive dechlorination of chlorobenzenes is analogous to reactions involving chlorinated ethenes and ethanes in that once dechlorination begins, the daughter compounds become increasingly amenable to aerobic biodegradation (Schraa *et al*., 1986; Spain and Nishino, 1987; Ramanand *et al*.,

1993). The reductive dechlorination of CB has not been documented; however, the structurally similar compound chlorotoluene has been observed to be dehalogenated to toluene in methanogenic soil slurries (Ramanand *et al.*, 1993).

4.3.4 Microbial Adaptation To Chlorinated Benzenes In The Field

Three proposed mechanisms are available to explain the adaptation of microbial communities to degrade chlorinated benzenes. These include: 1) chlorinated benzene-degrading microorganisms that exist below detection limits; 2) introduction of chlorinated benzene-degrading bacteria by dispersal from elsewhere; and 3) adaptation of indigenous, non-chlorinated benzene-degrading bacteria to enable degradation of chlorinated benzene through genetic changes. Numerous studies have documented the existence of chlorinated benzene-degrading bacteria at contaminated sites, primarily through the selective enrichment of groundwater or soil samples collected from the prospective site. However, recent studies suggest that indigenous bacteria typically are not capable of metabolizing chlorinated benzene, but become capable through the unique recombination (the exchange and incorporation of genetic information) between two separate bacterial types. For example, CB-degrading bacteria have been isolated after the mixing of a toluene-degrading strain and a chlorobenzoate-degrading strain and exposing the mixed cultures to CB vapors (Krockel and Focht, 1987).

CB-degrading bacteria observed at Site S-1 at Kelly AFB were detected only in contaminated wells and gene sequences between benzene/toluene-degrading bacteria and CB-degrading bacteria were similar (Van der Meer *et al.*, 1998). This is the first strong evidence for genetic recombination among bacteria in a groundwater aquifer resulting in the disappearance of chlorobenzenes from the environment. In the event of new spills in pristine areas, such gene modifications could require extensive lag times after contaminant release before CB degradation may occur.

The documented capability of indigenous microorganisms to aerobically degrade CB- and DCBs in unacclimated groundwater environments is generally observed only after an acclimation period. The length of this acclimation period may determine when and where natural attenuation begins at a CB spill site. In one study, nine months of selective enrichment were required through the incubation of benzene-degrading bacteria with increasing amounts of CB (Reineke and Knackmuss, 1984). Selective enrichments from soil and water samples have taken between 6 to 14 months to develop the ability to degrade 1,3-DCB, 1,4-DCB, 1,2-DCB, and 1,2,4-TCB (de Bont *et al*, 1986, Schraa *et al.*, 1986, Spain and Nishino, 1987, Haigler *et al.*, 1988, and van der Meer *et al.*, 1987).

Acclimated CB-degrading bacteria were detected in significant population numbers at four study sites contaminated for extended periods with CB, one of which was Site S-1 at Kelly AFB (Nishino *et al.*, 1994). On-site bioreactor studies were performed with two 135-L, pilot-scale, upflow, submerged bed bioreactors using groundwater from the shallow aquifer at Site S-1 to feed the system. Biofilms were established in the reactors using two different approaches. One reactor received an injection of Pseudomonas sp. Strain JS150, a CB-degrading strain with degradative pathways for a wide range of substituted aromatic compounds (Haigler *et al.*, 1992). This reactor was operated in a recycle mode for four days followed by four days of "fill and draw" mode with CB provided in the gaseous phase. The other reactor received a continuous flow of site groundwater for six days to allow natural colonization by indigenous microorganisms.

Follow-up laboratory studies were also performed using 1.2 Liter glass columns filled with carrier pellets. Indigenous CB-degrading bacteria for Site S-1 were measured at a population of 1.0×10^2 CB degraders per gram of contaminated soil and groundwater prior to the start of the study.

The bioreactors installed at Site S-1 by Nishino *et al.* (1994) removed most of the aromatic compounds from the influent groundwater within a 40-minute hydraulic residence time. After a 7-day acclimation period, the federal drinking water standard for CB of 100 μg/L was achieved in the reactor at hydraulic residence times as short as 30 minutes. This indicated that a strong, viable CB-degrading microbial population had pre-existed, or preacclimated, to CB at the site. When the supply of oxygen was reduced to the reactors, the breakthrough of CB occurred. This trend clearly indicated that aerobic biodegradation was responsible for the removal of CB in the reactor, and is likely the main biodegradation mechanism for removing CB contamination at Site S-1. No changes in CB degradation rates were observed when supplies of inorganic nutrients were discontinued to the reactors. This result indicates that groundwater at Kelly AFB had sufficient nutrients to maintain rapid aerobic biodegradation rates of CB and other compounds in the reactors. The process was limited only by oxygen concentrations. When a foreign CB-degrading strain of bacteria (JS150) was added to the reactors, these bacteria did not survive, but were displaced by more viable populations of indigenous Site S-1 bacteria. This result indicated that the artificial inoculation of other known strains of CB degrading bacteria would not benefit over the natural, preestablished Site S-1 microbial community. The results indicate the presence of an active CB-degrading bacteria limited only by lack of oxygen in groundwater at Site S-1.

BTEX were easily degraded in the laboratory columns constructed from Site S-1 soil and groundwater. CB and *o*-DCB also were easily degraded. The compound *p*-DCB was degraded a rates approximately 7 to 8 times slower than *o*-DCB or CB, respectively. However, a hydraulic residence time spanning several years at Site S-1 is sufficient time to mineralize *p*-DCB and other aerobically biodegradable compounds, despite relatively slow biodegradation rates.

The results obtained from Kelly AFB suggest that sites with chronic CB contamination may be ideally suited for the application of natural attenuation because indigenous microbial populations can immediately degrade migrating CB contaminants. A recent (acute) release of CB into an aquifer could experience a lengthy lag time before CB degradation could occur. Once microbial communities have adapted to the presence of CB, the biodegradation of CB may be limited only by the availability of electron acceptors and the prevailing site geochemistry. These possible site influences are discussed in the following sections.

4.3.5 Behavior of Chlorinated Benzene Plumes

In general, a sufficient amount of anthropogenic or natural carbon can drive the reducing potential of groundwater to levels appropriate for reductive dechlorination processes. This situation indicates that available DO has been consumed and the dominant microbial consortia are anaerobic. When dissolved carbon is unavailable to the microbial consortia, aerobic groundwater conditions may predominate.

4.3.6 Anaerobic Plume Behavior

Anaerobic plume behavior generally occurs where the primary substrate is either anthropogenic carbon (e.g., BTEX, landfill leachate, and DCB through TeCB) or natural carbon (e.g., lignen), and these carbon sources drive reductive dehalogenation by causing the depletion of dissolved oxygen. Therefore, anaerobic behavior is more likely at locations with a mixture of multiple carbon sources including chlorinated benzenes where the chlorinated benzenes from TCB to pentachlorobenzene may become susceptible to anaerobic degradation mechanisms (Holliger *et al.*, 1992; Ramanand *et al.*, 1993; Suflita and Townsend, 1995). Anaerobic groundwater plumes may be susceptible to the buildup of the daughter product CB which is not known to be susceptible to reductive dechlorination or anaerobic oxidation. When evaluating natural attenuation of an anaerobic plume, the following questions must be answered:

1) Does electron donor supply exceed demand (i.e., is the electron donor supply adequate)?

2) Will the microorganisms degrading the plume run out of highly chlorinated benzenes (electron acceptors) before it runs out of primary substrate (electron donors)?

3) What is the role of competing electron acceptors?

4.3.7 Aerobic Plume Behavior

Aerobic plume behavior dominates in areas that are characterized by low native and/or anthropogenic carbon concentrations, and DO concentrations that are greater than 1.0 mg/L. Under these conditions the plume is aerobic, and reductive dehalogenation will not occur. Thus, there is no reductive dechlorination of highly chlorinated benzenes to less chlorinated intermediates. Aerobically degradable compounds such as TeCB, TCB, DCB, and CB could be mineralized under aerobic conditions if appropriate microbial populations are present. Chlorinated benzene contamination, specifically CB contamination, could diminish under the effects of only dispersion and dilution at a new release site, although at a larger plume size, until the necessary enzyme systems are adapted in indigenous microbial communities.

4.3.8 Mixed Anaerobic and Aerobic Plume Behavior

A single chlorinated benzene plume can exhibit anaerobic and aerobic behavior in different portions of the plume. This can be beneficial for natural biodegradation of chlorinated benzene plumes. The best scenario involves a plume in which highly chlorinated benzenes (such as trichlorobenzene) are reductively dehalogenated (anaerobic source area), then daughter products such as DCB and CB are degraded aerobically (aerobic downgradient conditions). In this manner, all chlorinated benzene contamination would be susceptible to biodegradation and subsequent removal from the aquifer. However, the effectiveness of a mixed behavior environment is largely determined by the leaching rate of chlorinated benzenes to the aquifer. High leaching rates will promote a large anaerobic area which may deny the biodegradation of CB before a potential downgradient receptor is contacted. Furthermore, high or low levels of background DO in groundwater influence the rate at which oxygen is resupplied to the source area. High

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Aerobic plume behavior dominates in areas that are characterized by low native and/or anthropogenic carbon concentrations, and DO concentrations that are greater than 1.0 mg/L. Under these conditions the plume is aerobic, and reductive dehalogenation will not occur. Thus, there is no reductive dechlorination of highly chlorinated benzenes to less chlorinated intermediates. Aerobically degradable compounds such as TeCB, TCB, DCB, and CB could be mineralized under aerobic conditions if appropriate microbial populations are present. Chlorinated benzene contamination, specifically CB contamination, could diminish under the effects of only dispersion and dilution at a new release site, although at a larger plume size, until the necessary enzyme systems are adapted in indigenous microbial communities.

4.3.8 Mixed Anaerobic and Aerobic Plume Behavior

A single chlorinated benzene plume can exhibit anaerobic and aerobic behavior in different portions of the plume. This can be beneficial for natural biodegradation of chlorinated benzene plumes. The best scenario involves a plume in which highly chlorinated benzenes (such as trichlorobenzene) are reductively dehalogenated (anaerobic source area), then daughter products such as DCB and CB are degraded aerobically (aerobic downgradient conditions). In this manner, all chlorinated benzene contamination would be susceptible to biodegradation and subsequent removal from the aquifer. However, the effectiveness of a mixed behavior environment is largely determined by the leaching rate of chlorinated benzenes to the aquifer. High leaching rates will promote a large anaerobic area which may deny the biodegradation of CB before a potential downgradient receptor is contacted. Furthermore, high or low levels of background DO in groundwater influence the rate at which oxygen is resupplied to the source area. High

natural DO concentrations will help reduce the size of the anaerobic source area, and, therefore, increase the opportunity for the biodegradation of CB. Mixed behavior exists at Site S-1, which has high levels of organic carbon throughout the aquifer from past fuel and solvent contamination (a large part of which is CB). The source area contamination exerts a large biological oxygen demand that creates a path of low DO for at least 2,000 feet from the source area and promotes the extension of CB beyond the base perimeter (Section 4.4.2).

4.4 BIODEGRADATION OF BTEX

The biodegradation of common fuel constituents, such as the BTEX compounds, has been the subject of extensive research and is well documented. Numerous laboratory and field studies have shown that hydrocarbon-degrading bacteria can participate in the degradation of many of the chemical components of fuel hydrocarbons, including the BTEX compounds (Jamison et al., 1975; Atlas, 1981, 1984, 1988; Gibson and Subramanian, 1984; Reinhard et al., 1984; Young, 1984; Bartha, 1986; Wilson et al., 1986, 1987, and 1990; Barker et al., 1987; Baedecker et al., 1988; Lee, 1988; Chiang et al., 1989; Grbic-Galic, 1989 and 1990; Cozzarelli et al., 1990; Leahy and Colewell, 1990; Altenschmidt and Fuchs, 1991; Alvarez and Vogel, 1991; Baedecker and Cozzarelli, 1991; Ball et al., 1991; Bauman, 1991; Borden, 1991; Brown et al., 1991; Edwards & Grbic-Galic., 1992; Evans et al., 1991a and 1991b; Haag et al., 1991; Hutchins and Wilson, 1991; Hutchins et al., 1991a and 1991b; Beller et al., 1992; Bouwer, 1992; Edwards and Grbic-Galic, 1994; Thierrin et al., 1992; Malone et al., 1993; Davis et al., 1994). Fuel hydrocarbons biodegrade naturally when an indigenous population of hydrocarbon-degrading microorganisms is present in the aquifer and sufficient concentrations of electron acceptors and nutrients are available to these organisms.

During biodegradation of fuel hydrocarbons, the fuel compounds are used as electron donors. They are the primary substrate ("food") for the microbes, while the electron acceptors provide the oxidant used to reduce (metabolize) the substrate and produce energy. In most subsurface environments, both aerobic and anaerobic degradation of fuel hydrocarbons can occur, often simultaneously in different parts of the plume. The nearly ubiquitous nature of these processes is well documented (e.g., Rice et al., 1995; Wiedemeier et al., 1996; Kuehne and Buscheck, 1996, and Mace et al., 1997). Aerobic destruction of BTEX compounds dissolved in groundwater results in the consumption (reduction) of oxygen and the formation of carbon dioxide. Anaerobic destruction of the BTEX compounds is associated with the accumulation of fatty acids, production of methane, solubilization of iron, and reduction of nitrate and sulfate (Cozzarelli et al., 1990; Wilson et al., 1990).

4.5 DISTRIBUTION OF HYDROCARBONS AND DAUGHTER PRODUCTS

The first step for evaluating the occurrence and methods of biodegradation of chlorinated hydrocarbons and fuel hydrocarbons is to look at the distribution of target compounds and the products of biodegradation of those compounds. At many sites such as Site S-1, dissolved groundwater contamination consists of a mixture of compounds, some of which may be electron donors, some of which may be electron acceptors, and some of which may be either donors or acceptors. It is therefore important to evaluate the distribution of all relevant compounds and the spatial relationships between electron donors and electron acceptors.

For example, it is useful to determine if a source of dissolved electron donors (e.g., chlorobenzene and BTEX) coincides with a plume of dissolved contaminants that are most likely to be used as electron acceptors. The donors are needed to fuel biodegradation reactions that will either use some contaminants as electron acceptors or that will produce geochemical conditions that make the use of contaminants as electron acceptors more favorable. Also, because reductive dechlorination is the most common biodegradation reaction involving chlorinated hydrocarbons, it is useful to look for the presence of compounds that are most likely the product of biodegradation reactions, such as DCB or CB.

The following sections present contaminant and daughter product distributions at Site S-1, providing the initial evidence that chlorinated benzenes and dissolved fuel constituents are biodegrading. This evidence alone is not conclusive, but when combined with geochemical evidence presented in later sections, it is a significant indicator of biodegradation.

4.5.1 Fuel Hydrocarbons

Several compounds detected at Site S-1, such as BTEX, are typically considered contaminants. However, for the purposes of this discussion, BTEX are viewed differently because the focus of this work is on natural attenuation of the chlorinated benzenes. The presence of minor BTEX concentrations in the same area as DCB contamination plume creates favorable conditions for reductive dehalogenation, because the BTEX provide a source of electron donors and facilitate microbial reactions that reduce the local groundwater ORP. At Site S-1, BTEX concentrations are much lower than DCB or CB concentrations, and the extent and concentrations of the BTEX plume are such that detectable concentrations of BTEX compounds have not migrated to the extent of CB.

Experience implementing the AFCEE *Technical Protocol for Implementing Intrinsic Remediation with Long-Term Monitoring for Natural Attenuation of Fuel Contamination Dissolved in Groundwater* (Wiedemeier et al., 1995) at nearly 40 locations at Air Force Bases nationwide suggests that biodegradation of fuel hydrocarbons is essentially ubiquitous for a wide range of hydrogeologic settings. Also, data presented by Lawrence Livermore National Laboratories (LLNL) indicate that for over 1,000 sites with fuel hydrocarbon releases, 33 percent of the plumes were shrinking, 59 percent were stable, and only 8 percent were expanding, with most plumes less than 250 feet long (Rice et al., 1995). Unpublished data provided by Kuehne and Buscheck (1996) indicate similar trends, with 52 percent of plumes contracting, 35 percent stable, and 92 percent of the plumes being less than 200 feet long. Mace et al. (1997) present similar evidence for more than 600 sites in Texas. Therefore, a thorough demonstration of BTEX biodegradation and attenuation is less important relative to the need to demonstrate the use of MNA to address chlorinated benzenes dissolved in groundwater at Site S-1.

The low dissolved BTEX concentrations indicate that fuel constituents were released at relatively low concentrations at the site and/or a significant mass of BTEX (and other petroleum hydrocarbons) has been removed from groundwater through natural attenuation. The relatively low BTEX concentrations present at the site, in conjunction with electron acceptor and biodegradation byproduct data (discussed in following sections), indicate that biodegradation has contributed to removal of petroleum hydrocarbon mass. Other petroleum hydrocarbons (e.g., naphthalene) also will dissolve

into groundwater and undergo biodegradation. This evidence, coupled with evidence of the weathering of the source, provided the basis for not addressing natural attenuation of BTEX in the same detail as chlorinated benzenes.

4.5.1.1 Fuel Hydrocarbon Concentrations At Site S-1

The detection of fuel hydrocarbons at Site S-1 during the March/April sampling event was limited to benzene, toluene, naphthalene and TPH. A larger variety of BTEX compounds and chlorinated solvents may have been present, but could not be detected due to high analytical reporting limits. Therefore, a limited set of groundwater samples was collected in June 1998 with the intent of achieving lower analytical detection limits. As a result, a broader range of hydrocarbons was detected in samples collected in June 1998 which included the full range of BTEX compounds, isopropylbenzene, naphthalene, n-propylbenzene, 1,2,4-trimethylbenzene (TMB), and 1,3,5-TMB. With the exception of benzene and naphthalene, the concentrations of the fuel constituents in June 1998 were below 30 μg/L. Table 4.4 summarizes fuel hydrocarbons detected in groundwater as part of this study. With the exception of benzene and naphthalene, no fuel hydrocarbons were observed to migrate from the source area to beyond the Base perimeter fence. Figures 4.7 and 4.8 show groundwater benzene and naphthalene concentrations measured in March/April 1998 and June 1998, respectively.

Benzene concentrations measured in March/April were greater than measured in June 1998, ranging in concentration from 0.96 to 4,100 μg/L. The maximum benzene concentration of 4,100 μg/L was measured beneath the former sump area. Figure 4.7 indicates that the benzene plume migrates along the direction of groundwater flow to the northeast and extends more than 1,900 feet in that direction. Benzene concentrations decrease by approximately two orders of magnitude between the east/west array of groundwater extraction wells and monitoring wells SS003MW001 and SS003MW007, which are located along the longitudinal axis of the plume. Large benzene reductions in the 200 foot groundwater path between groundwater recovery well SS003RW202 (4,100 μg/L) and monitoring well SS003MW001 (24 μg/L) indicate the influence of the groundwater pump-and-treat system and/or natural attenuation.

Naphthalene concentrations were highest downgradient from the source area at monitoring well SS003MW273. This monitoring well is located approximately 30 feet southeast of recovery well SS003RW114 which contained free-product, a small percentage of which consisted of naphthalene. Naphthalene also was detected at monitoring well SS003MW001 (1.8 μg/L) indicating that trace levels of this compound have migrated off-base (Figure 4.8).

TABLE 4.4
FUEL CONSTITUENTS DETECTED IN GROUNDWATER
SITE S-1 MNA TS
KELLY AIR FORCE BASE, TEXAS

Sample ID	Date	Benzene (µg/L)[B]	Toluene (µg/L)	Ethyl-benzene (µg/L)	Xylenes (µg/L)	n-Propyl benzene (µg/L)	n-Butyl benzene (µg/L)	Naphthalene (µg/L)	1,2,4-trimethylbenzene (µg/L)	1,3,5-trimethylbenzene (µg/L)	TPH[A] (mg/L)[C]
SS003MW001	3/25/98	24	110 U	60 U	100 U	50 U	110 U	9.5 U	130 U	50 U	NA[D]
SS003MW001	6/18/98	1.5 J	5.5 U	3.0 U	5.0 U	2.5 U	5.5 U	1.8 J	6.5 U	2.5 U	NA
SS003MW004	3/28/98	71	39 U	21 U	36 U	8	39 U	9.5 U	46 U	18 U	1.2
SS003MW007	3/30/98	· 3.9	1.6	3.8 U	6.2 U	3.1 U	6.9 U	9.5 U	8.1 U	3.1 U	1 U
SS003MW008	3/29/98	12	18 U	10 U	17 U	8.3 U	18 U	9.5 U	22 U	8.3 U	.99
SS003MW008	6/18/98	0.5 U	1.1 U	0.6 U	1.0 U	0.5 U	1.1 U	1.0 U	1.3 U	0.5 U	NA
SS003MW009	3/31/98	.96	.16	0.6 U	1.0 U	0.5 U	1.1 U	1 U	1.3 U	0.5 U	NA
SS003MW010	3/30/98	1.4	.9	5 U	8.3 U	4.2 U	9.2 U	9.4 U	11 U	4.2 U	1 U
SS003MW010	6/18/98	0.5 U	1.1 U	0.6 U	1.0 U	0.48 J	1.1 U	1.0 U	1.3 U	0.5 U	NA
SS003MW011	3/30/98	2.4	.88	3 U	5.0 U	2.5 U	5.5 U	9.5 U	6.5 U	2.5 U	1 U
SS003MW013	3/24/98	5 U	11 U	6 U	10 U	5 U	11 U	9.5 U	13 U	5 U	NA
SS003MW016	3/30/98	1.5	.83	3.0 U	5.0 U	2.5 U	5.5 U	9.5 U	6.5 U	2.5 U	1 U
SS003MW016	6/18/98	0.5 U	0.3 J	0.6 U	1.0 U	0.5 U	1.1 U	1.0 U	0.11 J	0.5 U	NA
SS003MW018	3/30/98	1 U	2.2 U	1.2 U	2.0 U	1 U	2.2 U	9.4 U	2.6 U	1 U	.15
SS003MW019	3/26/98	4.9	5.5 U	3 U	5.0 U	2.5 U	5.5 U	5 U	6.5 U	2.5 U	NA
SS003MW020	3/28/98	33	37 U	20 U	33 U	17 U	37 U	9.5 U	43 U	17 U	.2
SS003MW050	3/24/98	1000	790 U	430 U	710 U	360 U	790 U	56	930 U	360 U	NA
SS003MW050	6/18/98	1300	5.6 J	30	7.8 J	28	55	12	5.6 J	25 U	NA
SS003MW053	3/28/98	2900	1400 U	750 U	1200 U	620 U	1400 U	1200 U	1600 U	620 U	NA
SS003MW053	6/19/98	3000 E	20 J	75	25 J	30 J	69 U	170	17 J	31 U	NA
SS003MW109	3/27/98	.5 U	1.1 U	0.6 U	1.0 U	0.5 U	1.1 U	1 U	1.3 U	0.5 U	NA
SS003MW110	3/27/98	520	340 U	190 U	310 U	160 U	340 U	310 U	410 U	160 U	NA
SS003MW115	3/26/98	150	92 U	50 U	83 U	15	92 U	83 U	110 U	42 U	NA
SS003MW116	3/26/98	3.5	9.2 U	5 U	8.3 U	4.2 U	9.2 U	8.3 U	11 U	4.2 U	NA
SS003MW120	3/27/98	720	280 U	150 U	250 U	120 U	280 U	410	320 U	120 U	NA
SS003MW120	6/19/98	690	28 U	5.0 J	3.1 J	24	19 J	33	32 U	12 U	NA
SS003MW121	3/29/98	1600	920 U	500 U	830 U	420 U	920 U	45	1100 U	420 U	NA
SS003MW202	3/27/98	4100	550 U	300 U	500 U	250 U	550 U	500 U	650 U	250 U	NA
SS003MW202	6/19/98	2600	110 U	60 U	100 U	32 J	110 U	49 J	130 U	50 U	NA
SS003MW272	4/1/98	1800	980	2500 U	4200 U	2100 U	4600 U	950 U	5400 U	2100 U	NA
SS003MW273	4/1/98	4100	4600 U	2500 U	4200 U	2100 U	4600 U	320	5400 U	2100 U	NA
SS003MW274	3/31/98	1000	1100 U	600 U	1000 U	500 U	1100 U	59	1300 U	500 U	NA
SS003MW274	6/18/98	1200	55 U	34	14 J	26	55 U	73	29 J	11 J	NA
SS003MW275	3/31/98	.5 U	1.1 U	0.6 U	1.0 U	0.5 U	1.1 U	9.4 U	0.21	0.5 U	NA

[A] TPH ~ Total Petroleum Hydrocarbons.

[B] µg/L ~ micrograms per liter.

[C] mg/L ~ milligrams per liter.

[D] NA ~ not analyzed or not available.

E~Estimated result; concentration exceeds the calibration range.

J~Estimated result; less than reporting limit.

U~ The analyte was analyzed for and is not present above the level of the associated value.
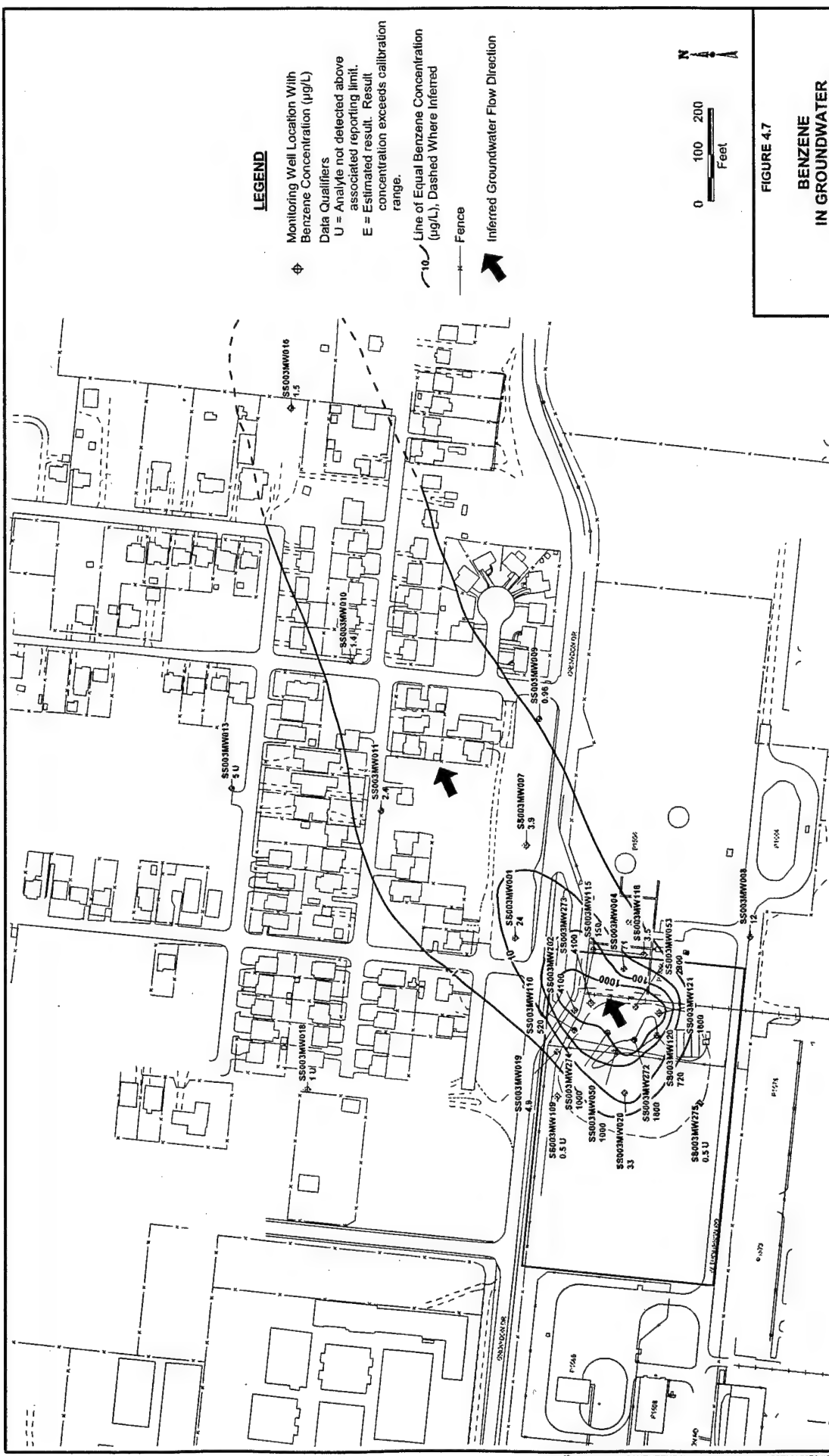
LEGEND

⊕ Monitoring Well Location With
Benzene Concentration (µg/L)
Data Qualifiers
U = Analyte not detected above
associated reporting limit.
E = Estimated result. Result
concentration exceeds calibration
range.

⌒10⌒ Line of Equal Benzene Concentration
(µg/L), Dashed Where Inferred

—x— Fence

◀ Inferred Groundwater Flow Direction
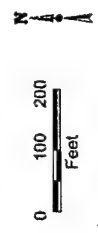
FIGURE 4.7

**BENZENE
IN GROUNDWATER
(MARCH/APRIL 1998)**

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.

Denver, Colorado

0   100   200
Feet

LEGEND

⊕ Monitoring Well Location With Napthalene Concentration (µg/L)

Data Qualifiers
U = Analyte not detected above associated reporting limit.
E = Estimated result. Result concentration exceeds calibration range.

↗10 Line of Equal Napthalene Concentration (µg/L), Dashed Where Inferred

✕ Fence

➜ Inferred Groundwater Flow Direction

FIGURE 4.8

**NAPTHALENE
IN GROUNDWATER
(JUNE 1998)**

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado

0 100 200
Feet

Of the 14 VOCs and SVOCs measured in LNAPL (Table 4.2), only four SVOCs were also not detected in groundwater. These compounds, including di-n-butyl phthalate, bis(2-ethylhexyl)phthalate, fluoranthene, and 2-methylnaphthalene are less soluble in water and were present in LNAPL at relatively low concentrations.

4.5.2 Chlorobenzene Concentrations

The CB groundwater plume observed in March/April 1998 is shown on Figure 4.9, and Table 4.5 summarizes CB data. The groundwater plume emanates from the former sump area and extends 2,000 feet to the northeast. Monitoring well SS003MW016 represents the furthest downgradient detection of CB (49 µg/L). CB concentrations have not been as high at SS003MW016 since October 1990 (600 µg/L) and the groundwater CB plume generally has maintained its current size since 1995.

The maximum CB concentration of 45,000 µg/L was detected at newly installed monitoring well SS003MW272. The location of this well is within both the former sump area and a pocket of mobile LNAPL contamination identified as part of this study (Section 4.1.1). Mobile LNAPL was not observed at this location in March/April 1998; however, a mobile LNAPL layer was detected in June 1998 (Section 4.1.1). Therefore, the maximum CB concentration at this location is consistent with the presence of significant residual and mobile LNAPL contamination.

High groundwater CB concentrations are not strictly confined to the defined limit of the former sump area as shown on Figure 4.9. For instance, groundwater from monitoring well SS003MW273, (located approximately 100 feet from the sump), contained CB at a concentration of 24,000 µg/L. Elevated CB concentrations outside of the former sump area are consistent with the observation of residual and mobile LNAPL migration to these locations. The steep sloping surface of the groundwater table is believed to have promoted the migration of mobile LNAPL from the former sump area to these locations.

CB concentrations decrease sharply downgradient from the groundwater pump-and-treat system (Figure 4.9). This decrease is likely due to extraction of contaminated water through recovery wells SS003RW113, -RW114, -RW115, and -RW116. Groundwater recovery well SS003RW114 has consistently produced the highest volume of water as compared to the other recovery wells and likely dewaters the aquifer close to the well (SAIC, 1996), helping minimize the propagation of CB contamination off-base.

An anomalous high chlorobenzene concentration of 200 µg/L was measured at monitoring well SS003MW008 in March/April 1998. This well is located approximately 200 feet southeast of the probable source area. The presence of CB contamination at this well suggests the presence of a smaller CB source peripheral to the main sump area. Groundwater CB concentrations measured 40.9 µg/L at this location in June 1996, and CB was not detected in June 1998. An anomalous increase in groundwater elevation also was measured at this location in March/April 1998 (Section 3.3.2.1). In addition, soil gas data collected in February 1998 (Section 4.1.2) indicate the presence of VOC contamination at least 100 feet southeast of the former sump area. The possibility exists that   a   secondary   source   of   CB   contamination   exists

TABLE 4.5
CHLORINATED SOLVENT CONSTITUENTS DETECTED IN GROUNDWATER
SITE S-1 MNA TS
KELLY AIR FORCE BASE, TEXAS

Sample ID	Date	1,2,3-TCB[A] (µg/L)[B]	1,2,4-TCB (µg/L)	1,2-DCB[A] (µg/L)	1,3-DCB (µg/L)	1,4-DCB (µg/L)	Chlorobenzene (µg/L)	PCE[A] (µg/L)	TCE[A] (µg/L)	cis-1,2-DCE[A] (µg/L)
SS003MW001	3/25/98	50 U[C]	9.5 U	9.5 U	9.5 U	9.5 U	790	140 U	100 U	120 U
SS003MW001	6/18/98	2.5 U	2.5 U	2.5 U	6.0 U	2.3 J	830 E[D]	7.0 U	5.0 U	5.9 J[E]
SS003MW004	3/28/98	18 U	9.5 U	9.5 U	9.5 U	9.5 U	510	50 U	36 U	43 U
SS003MW007	3/30/98	3.1 U	3.1 U	9.5 U	9.5 U	9.5 U	93	8.8 U	3.4	2.3
SS003MW008	3/29/98	8.3 U	8.3 U	9.5 U	9.5 U	9.5 U	200	23 U	5.3	1.9
SS003MW008	6/18/98	0.5 U	0.5 U	0.5 U	1.2 U	0.5 U	0.5 U	1.4 U	11	4.1
SS003MW009	3/31/98	0.5 U	0.5 U	.5 U	1.2 U	.5 U	13	1.4 U	.84	.48
SS003MW010	3/30/98	4.2 U	4.2 U	9.4 U	9.4 U	9.4 U	45	12 U	8.3 U	1.8
SS003MW010	6/18/98	0.5 U	0.5 U	0.5 U	1.2 U	0.5 U	4.9	1.4 U	0.34 J	1.2
SS003MW011	3/30/98	1	2.5 U	9.5 U	9.5 U	9.5 U	89	7 U	.79	.65
SS003MW013	3/24/98	5 U	5 U	9.5 U	9.5 U	9.5 U	5 U	190	27	14
SS003MW016	3/30/98	2.5 U	2.5 U	9.5 U	9.5 U	9.5 U	49	3.8	5 U	6 U
SS003MW016	6/18/98	0.5 U	0.5 U	0.5U	1.2 U	0.5 U	0.5 U	7.2	0.59 J	0.76 J
SS003MW018	3/30/98	1 U	1 U	9.4 U	9.4 U	9.4 U	1 U	21	1.4	4.1
SS003MW019	3/26/98	2.5 U	2.5 U	2.5 U	6 U	1.6	62	7 U	5 U	6 U
SS003MW020	3/28/98	17 U	9.5 U	9.5 U	9.5 U	9.5 U	400	7.8	33 U	40 U
SS003MW050	3/24/98	360 U	9.6 U	37	7.5	58	11000	1000 U	710 U	860 U
SS003MW050	6/18/98	25 U	25 U	97	19 J	150	14000 E	70 U	50 U	8.8 J
SS003MW053	3/28/98	620 U	620 U	620 U	1500 U	140	22000	1800 U	1200 U	1500 U
SS003MW053	6/19/98	31 U	31 U	14 J	75 U	150	17000 E	88 U	62 U	180
SS003MW109	3/27/98	0.5 U	0.5 U	.5 U	1.2 U	.5 U	2.6	.46	1.4	2.5
SS003MW110	3/27/98	160 U	160 U	160 U	380 U	160 U	5400	440 U	310 U	380 U
SS003MW115	3/26/98	42 U	42 U	42 U	100 U	42 U	920	120 U	83 U	100 U
SS003MW116	3/26/98	4.2 U	4.2 U	4.2 U	10 U	4.2 U	150	.99	8.3 U	10 U
SS003MW120	3/27/98	120 U	120 U	46	300 U	40	4200	350 U	250 U	300 U
SS003MW120	6/19/98	12 U	12 U	250	35	150	5200 E	35 U	25 U	3.3 J
SS003MW121	3/29/98	420 U	9.5 U	9.5 U	6.2	38	14000	1200 U	830 U	1000 U
SS003MW202	3/27/98	250 U	250 U	250 U	600 U	250 U	8100	700 U	500 U	600 U
SS003MW202	6/19/98	50 U	50 U	18 J	120 U	11 J	5000 E	140 U	100 U	120 U
SS003MW272	4/1/98	2100 U	950 U	10000	630	2900	45000	5800 U	4200 U	1300
SS003MW273	4/1/98	2100 U	38 U	38 U	38 U	27	24000	5800 U	4200 U	5000 U
SS003MW274	3/31/98	500 U	500 U	300	29	29	12000	1400 U	1000 U	1200 U
SS003MW274	6/18/98	18 J	24 J	5300	310	900	20000 E	NA[F]	NA	NA
SS003MW274	6/18/98	18 J	24 J	4900 E	310	900	13000 E	70 U	50 U	19 J
SS003MW275	3/31/98	0.5 U	0.5 U	9.4 U	9.4 U	9.4 U	.5 U	1.4 U	.14	1.2 U

[A] DCB = Dichlorobenzene
DCE = Dichloroethene
PCE = Tetrachloroethene
TCB = Trichlorobenzene
TCE = Trichloroethene
TPH = Total Petroleum Hydrocarbons

[B] µg/L = micrograms per liter.

[C] U = The analyte was not present above the associated reporting limit.

[D] E=Estimated result exceeding the calibration range.

[E] J=Estimated result less than reporting limit.

[F] NA = Not analyzed.

Note: All samples were analyzed in accordance with Test Methods for Evaluating Solid Wastes, SW-846, Third Edition (USEPA, 1996b), or Methods for Chemical Analysis of Water and Wastes, Third Edition (USEPA, 1983).

FILE S:\ES\REMEDI\BIOPLUME\732351\KELLY\REPORT\FIGURES\CB.WOR 08/13/96 @ 1051
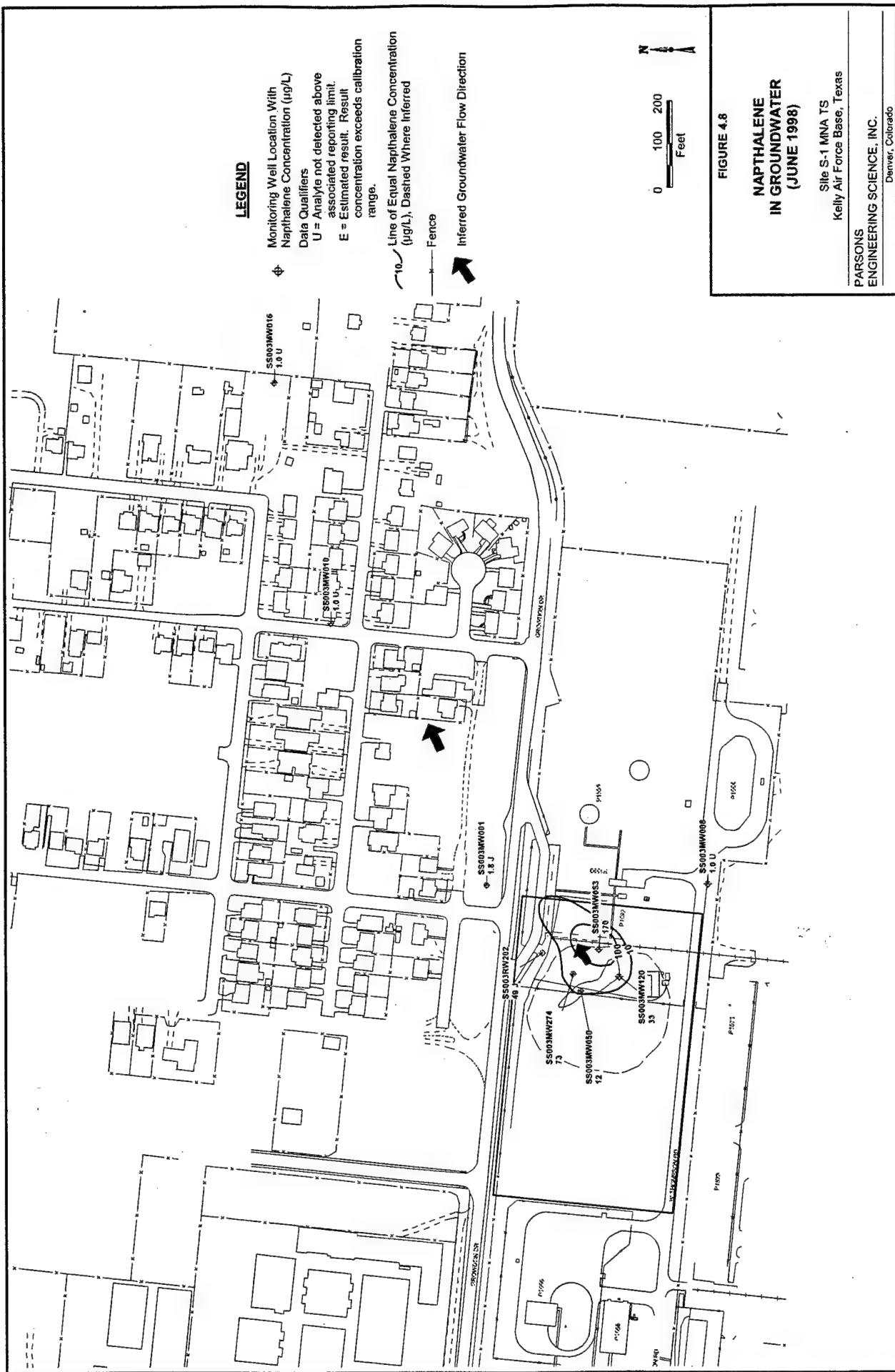
LEGEND

⊕ Monitoring Well Location With
    Chlorobenzene Concentration (µg/L)

    Data Qualifiers
    U = Analyte not detected above
        associated reporting limit.
    E = Estimated result. Result
        concentration exceeds calibration
        range.

10 Line of Equal Chlorobenzene Concentration
    (µg/L), Dashed Where Inferred

——×—— Fence

    Inferred Groundwater Flow Direction

FIGURE 4.9

CHLOROBENZENE
IN GROUNDWATER
(MARCH/APRIL 1998)

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.

Denver, Colorado

0   100   200
Feet
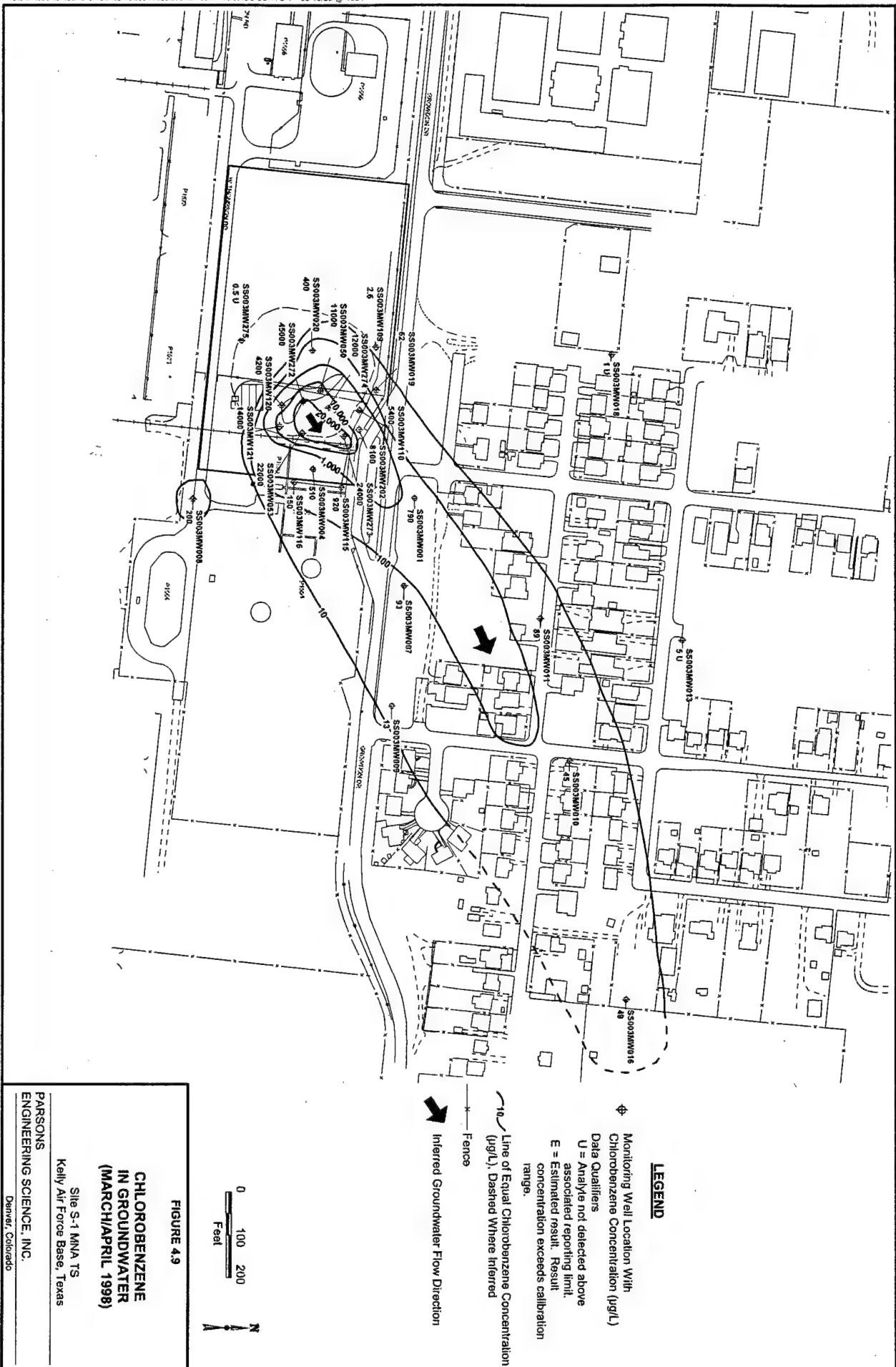
near monitoring well SS003MW008 that could contribute to low-level groundwater contamination during high-water periods.

The groundwater CB plume at Site S-1 is much smaller than observed since 1989 and the length of the plume has stabilized to a much shorter length. Recently, the groundwater CB plume measured in June 1998 (Figure 4.10) appears to be shorter than measured in March/April 1998 (Figure 4.9) and illustrates fluctuation of the plume length due to seasonal variation. In contrast, groundwater concentrations increased between the time from March/April 1998 to June 1998 at monitoring wells SS003MW001, -MW050, -MW120, and -MW274. However, the current CB plume is at least 1,000 feet shorter than observed a decade ago.

Increases in CB concentration in the source area between March/April and June 1998 occurred during a period of low rainfall rates. For instance, monthly rainfall for February and March 1998 were 3.38 and 2.85 inches, respectively, versus 0.05 and 0.34 inches for April and May 1998, respectively. Groundwater elevations had decreased by approximately 1 foot between March/April 1998 and June 1998. It is possible that CB concentrations in the source area are increased during periods of low precipitation and groundwater recharge as CB concentrations become more concentrated.

Figure 4.11 presents a historic summary of groundwater contamination along the centerline of the CB plume. CB concentrations at downgradient and off-base monitoring wells (e.g., SS003MW001, SS003MW010, SS003M011, and SS003MW016) declined from 1989 to 1995, prior to the installation of the groundwater pump and treat system. CB concentrations measured at downgradient well SS003MW016, which is in the direct path of plume migration and approximately 1,500 feet from the source area, have fluctuated between 0 and 49 $\mu g/L$ between December 1995 and June 1998. Other downgradient monitoring wells closer to the base (e.g., SS003MW001 and SS003MW010) also have exhibited contaminant concentration fluctuations since 1995, but with no clear trend toward increase or decrease.

The substantial CB reductions at downgradient wells at Site S-1 between 1989 and 1995 suggest that significant rates of source weathering and/or natural attenuation of dissolved CB were occurring during this period. The order of magnitude reduction in downgradient CB concentrations suggest that source leaching rates have similarly decreased. However, a trend of decreasing CB leaching rates in the source area is not supported by groundwater analytical data. Furthermore, no significant source remediation or construction and digging activities were performed between 1989 and 1997. Therefore, the significant declines in dissolved CB may be the result of natural source weathering and groundwater CB attenuation, or by some other unidentified process.

The size, length, and concentration of the CB plume may strongly be affected by variations in water levels and flushing rates caused by fluctuating precipitation rates. For instance, groundwater elevations in 1992 at Site S-1 were at least 4 feet higher than presently observed and would alter the leaching rates and dilution capability of the aquifer (see Section 3.3.1.1). However, the lack of groundwater data between 1990 and 1995 and the installation of the groundwater pump and treat system in 1995 obscures the verification of such trends. Although chronic CB contamination has been

LEGEND

$\oplus$ Monitoring Well Location With
     Chlorobenzene Concentration (µg/L)
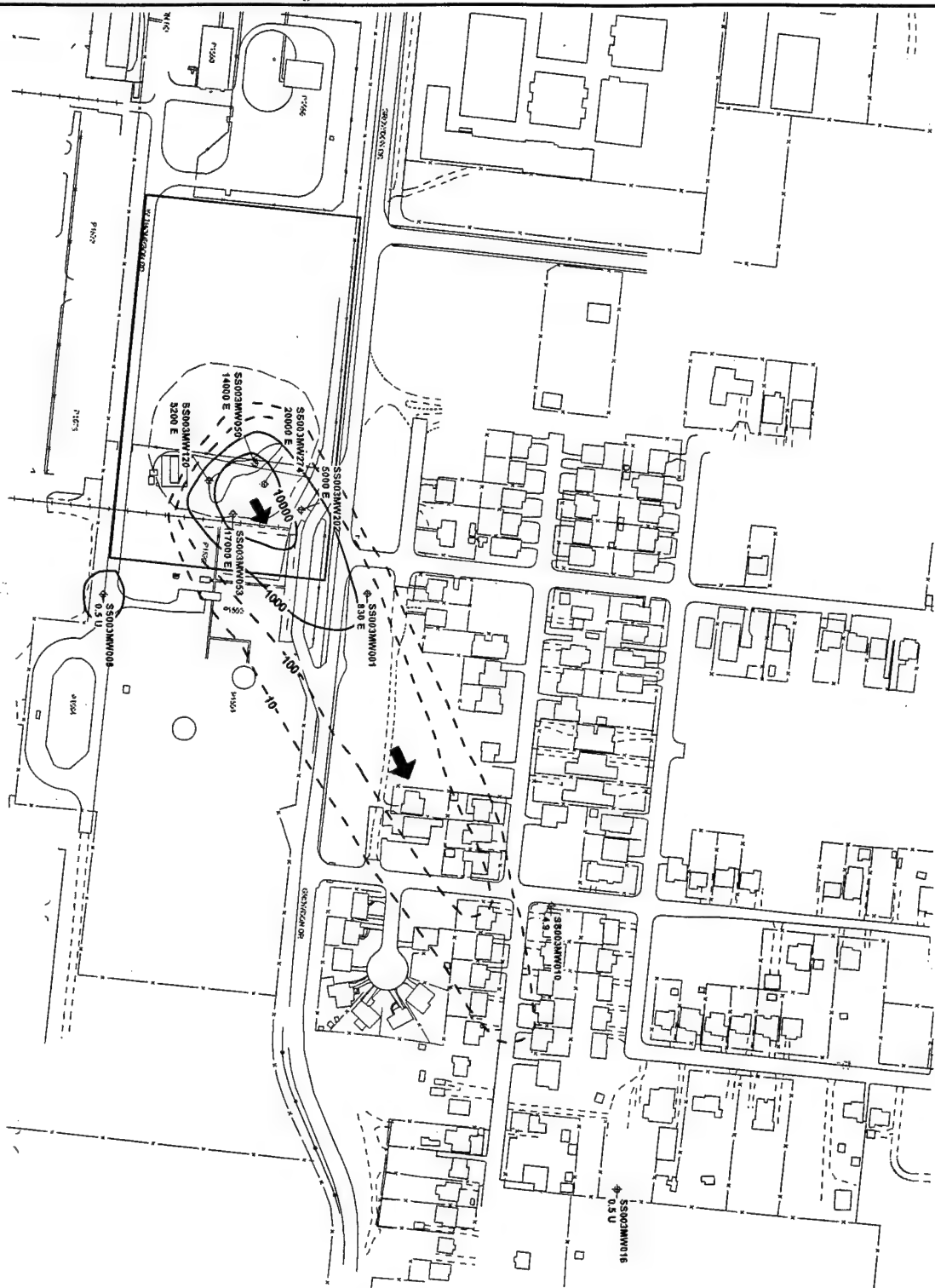
Data Qualifiers
   U = Analyte not detected above
      associated reporting limit.
   E = Estimated result. Result
      concentration exceeds calibration
      range.

~10~   Line of Equal Chlorobenzene Concentration
      (µg/L). Dashed Where Inferred

—x—   Fence

⟶   Inferred Groundwater Flow Direction

0   100   200

Feet

N

FIGURE 4.10

CHLOROBENZENE
IN GROUNDWATER
(JUNE 1998)

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.

Denver, Colorado

HISTORICAL CHLOROBENZENE
CONCENTRATION TRENDS

Site S-1 MNA TS
Kelly Air Force Base, Texas

FIGURE 4.11

PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado
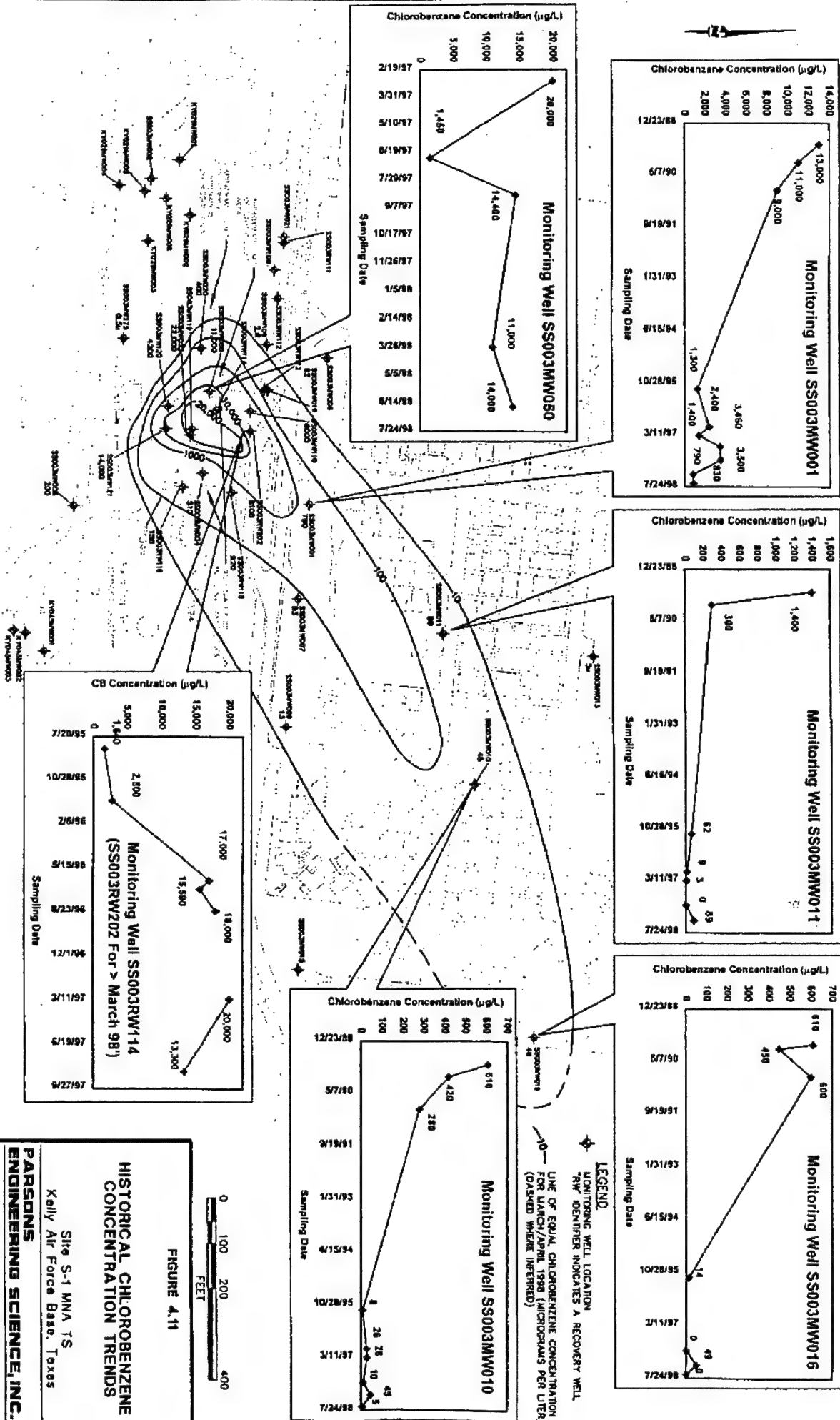
present at Site S-1 for at least three decades, it is possible that significant natural attenuation of the groundwater plume through biodegradation did not begin to destroy contaminant mass until the 1980's. Microbial acclimation to CB contamination through the process of genetic recombination requires that both structurally similar contaminants are present and that an indigenous population exists to biodegrade these contaminants. Under these conditions, microbial induction may occur and biodegradation of CB at a site is possible (Van der Meer *et al.*, 1998). This adaptation may have taken several decades at Site S-1, although historic data are insufficient to support this observation.

4.5.3 Trichlorobenzene and Dichlorobenzene Contamination

The compound 1,2,4-TCB was detected in mobile LNAPL samples collected at the site, but was detected in groundwater from only a single monitoring well in June 1998 (24 μg/L at SS003MW274). Concentrations of 1,2,4-TCB likely were present at monitoring well SS003MW272 in March/April 1998 at a concentration below the analytical reporting limit. The compound 1,2,3-TCB was detected at monitoring well SS003MW272 in June 1998 (18 μg/L) though it was not detected in mobile LNAPL samples collected as part of this study.

DCB was a significant constituent of the mobile LNAPL samples and was also detected in groundwater samples. The DCB isomers 1,2-DCB, 1,3-DCB, and 1,4-DCB all were detected in groundwater samples collected in March/April 1998 and June 1998 in the former sump area (Figure 4.12). Similar to CB, DCB concentrations increased between March/April 1998 and June 1998.

Of the three DCB isomers detected at Site S-1, 1,2-DCB was present at the highest concentrations in both mobile LNAPL (Table 4.2) and groundwater. The maximum 1,2-DCB concentration of 10,000 μg/L was detected at monitoring well SS003MW272. Beyond this location, 1,2-DCB concentrations rapidly diminish and were not detected above the analytical reporting limit of 38 μg/L at monitoring well SS003MW273, which contained CB contamination in excess of 20,000 μg/L. The areal dimensions of the 1,2-DCB plume were similar between March/April 1998 and June 1998; both plumes were approximately 140 feet wide by 200 feet long.

1,4-DCB was the chlorinated benzene compound detected at the third highest concentration (behind CB and 1,2-DCB) in both mobile LNAPL and groundwater at the site. The maximum 1,4-DCB concentration of 2,900 μg/L was detected at monitoring well SS003MW272. The maximum 1,3-DCB concentration of 630 μg/L also was detected at this location.

The areal extent of DCB in groundwater is relatively small compared to that of CB (compare Figures 4.12 and Figures 4.9). The rapid disappearance of DCB prior to reaching the northern base boundary and the presence of elevated CB concentrations is strong evidence that DCB is being reductively dechlorinated to CB. The amount of CB that is attributable to reductive dechlorination of DCB cannot be distinguished for two reasons: 1) CB also is a primary contaminant source at Site S-1 based on high CB concentrations observed in LNAPL samples (see Section 4.1.1); and 2) the fraction of CB in the source area likely is spatially variable.

LEGEND

⊕ Monitoring Well Location With
Dichlorobenzene Concentration (µg/L)

Data Qualifiers
U = Analyte not detected above
associated reporting limit.
E = Estimated result. Result
concentration exceeds calibration
range.

⌒10⌒ Line of Equal Dichlorobenzene Concentration
(µg/L), Dashed Where Inferred

✕ Fence

← Inferred Groundwater Flow Direction

FIGURE 4.12

**DICHLOROBENZENES
IN GROUNDWATER
(MARCH/APRIL AND JUNE 1998)**

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.

Denver, Colorado

1,2-DICHLOROBENZENE
(June 1998)

1,3-DICHLOROBENZENE
(June 1998)

1,4-DICHLOROBENZENE
(June 1998)

1,2-DICHLOROBENZENE
(April/May 1998)

1,3-DICHLOROBENZENE
(April/May 1998)

1,4-DICHLOROBENZENE
(April/May 1998)

4.5.4 Chlorinated Ethene Contamination

Chlorinated ethenes in the form of PCE, TCE, DCE, and VC historically have been detected in groundwater at Site S-1, but at much lower concentrations then chlorinated benzenes or benzene. The presence of dissolved PCE and TCE in monitoring wells located cross-gradient from the CB plume indicate the presence of at least two chlorinated ethene sources unrelated to Site S-1 contamination. For instance, in March/April 1998, the highest concentration of PCE (190 µg/L) occurred at monitoring well SS003MW013, which is north of the existing CB plume. The most elevated detections of PCE, TCE, or DCE in groundwater in March/April 1998 occurred in groundwater from monitoring wells downgradient from the extraction well system and north of the CB plume (i.e., SS003MW007, SS003MW011, SS003MW018, and SS003MW013) and southwest of the plume (e.g., monitoring well SS003MW008). Low-level detections of chlorinated ethenes occurred at monitoring wells SS003MW116, -MW020, and -MW109 during the March/April 1998 sampling event, indicating the presence of trace concentrations of chlorinated ethene in the source area. Chlorinated ethenes were not detected above analytical detection limits in mobile LNAPL samples collected from monitoring wells SS003MW272 or SS003RW114. Vinyl chloride was not detected in any samples collected during this study.

Historical analytical data from monitoring well SS003MW001 (see summary table in Appendix A) indicates that detectable concentrations of TCE and PCE have not migrated beyond this location. Therefore, low-level PCE and TCE contamination originating at Site S-1 appears to attenuate to non-detectable levels prior to off-base migration. The attenuation of PCE and TCE provides additional evidence that reductive dechlorination may be the primary biological degradation pathway for chlorinated compounds within the source area. Off-base concentrations of PCE and TCE appear to be related to unidentified off-base sources migrating into the vicinity of Site S-1 from the northwest or southeast. Similar distributions were observed in 1989/1990 and summarized in the groundwater FFS report (HNUS, 1994)

4.5.5 Chloride

Chloride ions are removed from chlorinated solvents and enter solution during biodegradation, whether via reductive dehalogenation or aerobic oxidation. Therefore, chloride concentrations in groundwater should increase above background levels in areas where significant reductive dehalogenation or aerobic biodegradation is taking place. Chloride concentrations are presented in Table 4.6, and Figure 4.13 shows the March/April 1998 distribution of chloride in shallow groundwater at the site. Background chloride concentrations (measured in "clean" wells upgradient or crossgradient from the contaminant plume) averaged approximately 5.7 mg/L. Chloride concentrations in groundwater nearest to the former sump area are elevated above 20 mg/L, with a maximum chloride concentration of 124 mg/L at SS003MW272.

In conjunction with the distributions of chlorinated benzene compounds shown on Figures 4-9 to 4-12, the elevated chloride concentrations observed at Site S-1 are a good indication that chlorinated solvent contamination is undergoing microbially mediated degradation. It is particularly noteworthy that the highest chloride concentrations occur at and downgradient from SS003MW272, where the highest CB and DCB concentrations were detected.

TABLE 4.6
GROUNDWATER ELECTRON ACCEPTORS/BYPRODUCTS
SITE S-1 MNA TS
KELLY AIR FORCE BASE, TEXAS

Sample ID	Date Sampled	Dissolved Oxygen (mg/L)[a]	Nitrate as Nitrogen (mg/L)	Ferrous Iron (mg/L)	Total Iron (mg/L)	Sulfate (mg/L)	Hydrogen Sulfide (mg/L)	Carbon Dioxide (mg/L)	Ethane (µg/L)[b]	Ethene (µg/L)	Methane (µg/L)	Chloride (mg/L)
SS003MW001	3/25/98	0.80	.5 U[c]	4.85	4.90	4.8	0	85	.5 U	.5 U	2	26.6
SS003MW004	3/28/98	0.40	.5 U	4.18	4.72	.85	0.7	60	.31	.5 U	660	5.3
SS003MW007	3/30/98	0.40	1.5	0.75	0.20	11.2	1.4	100	.15	.5 U	300	7.7
SS003MW008	3/29/98	0.80	4.8	0.05	0.14	15.2	0	100	.5 U	.5 U	.7	6.7
SS003MW009	3/30/98	0.40	NA[d]	0.07	0.03	NA	NA	80	.5 U	.5 U	.3	NA
SS003MW010	3/30/98	0.20	1.3	0.53	0.00	12.1	NA	120	.5 U	.5 U	11	7.5
SS003MW011	3/30/98	1.00	1.1	0.20	0.04	11.3	NA	100	.5 U	.5 U	4.6	7.2
SS003MW013	3/24/98	7.03	6.1	0.10	0.13	49.7	0.017	40	.5 U	.5 U	.15	27.4
SS003MW016	3/30/98	0.30	.98	0.09	0.10	15.1	NA	90	.5 U	.5 U	6.4	14.4
SS003MW018	3/30/98	2.60	2.6	0.07	0.00	21.6	NA	40	.5 U	.5 U	.38	14.1
SS003MW019	3/25/98	0.24	.5 U	2.32	2.44	10.4	0.9	80	.5 U	.5 U	25	14.4
SS003MW020	3/27/98	0.50	2.5	0.49	0.63	20	1.6	100	.5 U	.11	12	5.9
SS003MW050	3/24/98	0.45	.5 U	5.48	10.68	5 U	0.01	70	1.6	.5 U	2100	15
SS003MW053	3/28/98	0.50	.5 U	11.61	10.92	1.1	2.7	99	13	.5 U	5700	36.8
SS003MW109	3/26/98	2.82	1.5	0.16	16.28	14.5	0.132	60	.5 U	.5 U	.19	9.3
SS003MW110	3/27/98	0.05	.5 U	10.29	12.48	5 U	0.2	70	.59	.13	860	9.6
SS003MW115	3/26/98	0.49	.097	5.42	8.38	5 U	0.3	70	.18	.5 U	290	6.3
SS003MW116	3/26/98	4.12	.35	0.22	0.16	4.7	0.8	21	.5 U	.5 U	30	3.1
SS003MW120	3/27/98	0.40	.5 U	12.78	13.96	.79	1.6	104	1.1	.22	3300	11.7
SS003MW121	3/29/98	0.10	.5 U	12.36	15.32	.53	0	140	1.9	.15	5300	22.1
SS003MW202	3/27/98	0.40	.5 U	13.71	15.20	.71	0.3	111	1.3	.5 U	1300	14.4
SS003MW272	4/1/98	0.40	.1	12.80	15.28	.8	NA	160	2.6	2.7	4800	124
SS003MW273	4/1/98	0.40	.16	12.60	12.15	2.1	NA	100	5.7	1.3	2500	46.6
SS003MW274	3/31/98	1.90	.13	3.61	4.15	5.8	NA	160	.87	1.1	530	26.7
SS003MW275	3/31/98	6.25	2.2	0.00	0.16	24.8	NA	52	.5 U	.5 U	.2	4.7

[a] mg/L = milligrams per liter.

[b] µg/L = micrograms per liter.

[c] U = The analyte was analyzed for and is not present above the associated reporting limit.

[d] NA = Not analyzed.

Note: All samples were analyzed in accordance with Test Methods for Evaluating Solid Wastes, SW-846, Third Edition (USEPA, 1996b),

Methods for Chemical Analysis of Water and Wastes, Third Edition (USEPA, 1983) and RSK 175 Standard Operating Procedures.
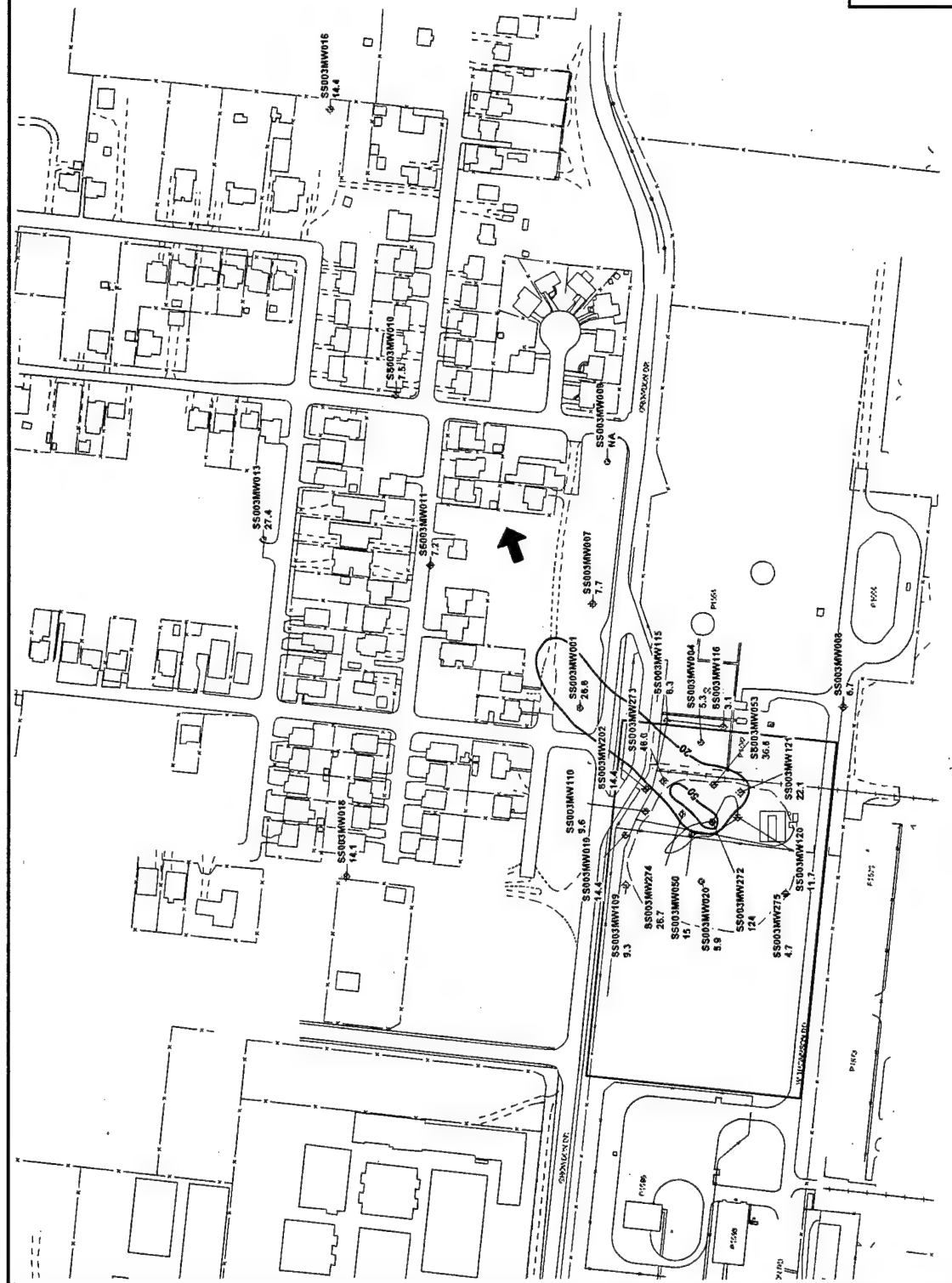
LEGEND

⊕ Monitoring Well Location With Chloride Concentration (mg/L)

Data Qualifiers
U = Analyte not detected above associated reporting limit.
E = Estimated result. Result concentration exceeds calibration range.

⌒10⌒ Line of Equal Chloride Concentration (mg/L), Dashed Where Inferred

×—×—× Fence

➡ Inferred Groundwater Flow Direction
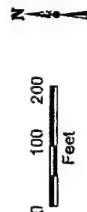
FIGURE 4.13

**CHLORIDE
IN GROUNDWATER
(MARCH/APRIL 1998)**

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.

Denver, Colorado

0   100   200
Feet

SS003MW016
14.4

SS003MW010
17.5

SS003MW009
NA

SS003MW013
27.4

SS003MW011
7.2

SS003MW007
7.7

SS003MW018
14.1

SS003MW001
26.8

SS003MW115
SS003MW004
5.3
SS003MW116
3.1

SS003MW053
SS003MW008
6.7

SS003MW273
46.0

SS003MW202
14.6

SS003MW121
36.6

SS003MW124
22.1

SS003MW110

SS003MW019
9.6

SS003MW109
14.4

SS003MW020
5.9

SS003MW120

SS003MW123
4.7

SS003MW274
26.7

SS003MW050
15

SS003MW272
124

SS003MW275
11.7

SS003MW109
9.3

4.6 ADDITIONAL EVIDENCE OF BIODEGRADATION

As noted in Section 4.3, comparing concentrations and distributions of electron donors, electron acceptors, and byproducts of microbially mediated reactions can help indicate the types of processes operating at a site. In addition, other geochemical parameters, including ORP, alkalinity, and other changes in groundwater chemistry can provide supporting evidence.

4.6.1 Electron Donors, Native Electron Acceptors, and Byproducts

When investigating the biodegradation of hydrocarbons and solvents, it is informative to evaluate the distribution of other compounds that are used in or produced by the microbially mediated reactions that facilitate contaminant degradation. The distribution of potential electron donors other than contaminants, such as dissolved native organic carbon, is useful for evaluating the feasibility of reductive dehalogenation or cometabolism (i.e., biodegradation reactions involving another substrate). Moreover, electron acceptor and metabolic byproduct data can clarify which processes may be facilitating contaminant degradation.

4.6.1.1 Organic Carbon in Groundwater

Dissolved organic carbon (DOC) can act as a source of electron donors during the reductive dehalogenation of DCB, or other contaminants such as TCE and DCE. DOC data from wells outside contaminant plumes can be used as an indicator of background levels of native carbon compounds.

DOC data measured in groundwater at Site S-1 are presented in Table 4.7 and shown on Figure 4.14. DOC concentrations detected in shallow groundwater at Site S-1 range from 0.63 to 206 mg/L. The highest concentration was measured at SS003MW272 and reflects the presence of substantial soil and groundwater contamination at that location. Elsewhere, the DOC concentrations did not exceed 29 mg/L. Background DOC concentrations measured at monitoring wells SS003MW275 and SS003MW008 averaged 1.1 mg/L. DOC concentrations within or downgradient from the source exceeded this background value at all locations but one (SS003MW018) area (Figure 4.14).

Native DOC provides a source of up to 1.1 mg/L of additional organic matter that is available for use as a substrate in biodegradation reactions. The background concentrations likely represent carbon dissolved from organic matter dispersed throughout the aquifer. In addition to soil TOC, this carbon source should provide a potential source of electron donors to fuel microbial redox reactions.

4.6.1.2 Inorganic Chemistry

An interpretation of inorganic groundwater geochemistry, including isopleth maps for typical electron acceptors, can provide information regarding the relative importance of various biodegradation mechanisms and whether the conditions at the site are favorable for reductive dehalogenation of chlorinated compounds. Numerous geochemical parameters were evaluated in site groundwater samples. Analytical results for geochemical various parameters measured in site samples are presented in

TABLE 4.7
GROUNDWATER GEOCHEMICAL DATA
SITE S-1 MNA TS
KELLY AIR FORCE BASE, TEXAS

Sample ID	Date Sampled	Alkalinity, Total as CaCO3 (mg/L)[a]	Dissolved Organic Carbon (mg/L)	Total Organic Carbon (mg/L)	Conductivity (µS/cm)[b]	Temperature (°C)[c]	pH	Redox (mV)[d]
SS003MW001	3/25/98	440	3.2	NA[e]	460	25.8	6.5	-3.2
SS003MW004	3/28/98	321	2.2	NA	605	23.6	7.0	-128.7
SS003MW007	3/30/98	389	.63	NA	780	24.6	6.9	93.8
SS003MW008	3/29/98	389	.97	NA	803	26.2	6.8	182.2
SS003MW009	3/30/98	NA	NA	NA	847	25.3	6.8	40.2
SS003MW010	3/30/98	373	.52	NA	741	24.8	6.9	106.0
SS003MW011	3/30/98	366	1 U	NA	722	25.0	6.9	154.6
SS003MW013	3/24/98	338	.76	.34	804	23.5	6.4	68.0
SS003MW016	3/30/98	375	.98	NA	763	23.5	6.9	125.0
SS003MW018	3/30/98	358	1.2	NA	660	22.4	7.0	154.0
SS003MW019	3/25/98	435	2.2	NA	887	23.2	6.6	-50.5
SS003MW020	3/27/98	431	2.4	NA	850	25.3	6.7	122.8
SS003MW050	3/24/98	426	9.1	11.5	806	25.2	8.7	-228.0
SS003MW053	3/28/98	503	29	NA	1074	24.0	6.7	-132.7
SS003MW109	3/26/98	397	.78	NA	805	24.6	6.6	109.5
SS003MW110	3/27/98	382	5.4	NA	779	23.7	6.7	-165.4
SS003MW115	3/26/98	324	3.9	NA	645	22.8	6.9	-82.1
SS003MW116	3/26/98	215	1.4	NA	413	21.7	7.2	126.6
SS003MW120	3/27/98	360	6.5	NA	695	24.3	6.8	-185.3
SS003MW121	3/29/98	409	4.6	NA	861	23.3	6.8	-216.8
SS003MW202	3/27/98	407	8.6	NA	806	24.9	6.7	-172.8
SS003MW272	4/1/98	605	206	NA	1452	23.5	6.8	-73.0
SS003MW273	4/1/98	438	27.4	NA	928	22.8	6.8	-200.0
SS003MW274	3/31/98	466	22	NA	901	22.8	6.8	45.0
SS003MW275	3/31/98	308	1.2	NA	645	22.3	7.0	286.0

[a] mg/L = milligrams per liter, CaCO3 = calcium carbonate.

[b] µS/cm = microsiemens per centimeter.

[c] °C = Degrees celcius.

[d] mV = millivolts.

[e] NA = Not analyzed.

Note: All samples were analyzed in accordance with Test Methods for Evaluating Solid Wastes, SW-846, Third Edition (USEPA, 1996b), and Methods for Chemical Analysis of Water and Wastes, Third Edition (USEPA, 1983).

LEGEND

⊕ Monitoring Well Location With Dissolved
Organic Carbon Concentration (mg/L)

Data Qualifiers
U = Analyte not detected above
associated reporting limit.
E = Estimated result. Result
concentration exceeds calibration
range.

⟋10⟍ Line of Equal Dissolved Organic
Carbon Concentration (mg/L),
Dashed Where Inferred

—×— Fence

◄ Inferred Groundwater Flow Direction

FIGURE 4.14

DISSOLVED ORGANIC CARBON
IN GROUNDWATER
(MARCH/APRIL 1998)

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE. INC.

Denver, Colorado

0   100   200

Feet

Tables 4.6 and 4.7. The following paragraphs discuss those parameters that are most useful in the evaluation of site biodegradation processes.

4.6.1.2.1 Dissolved Oxygen

DO concentrations measured at monitoring wells during the March/April 1998 sampling event indicate anaerobic conditions present throughout most of the groundwater plume. Concentrations ranged from 0.1 to 7.03 mg/L (Table 4.6), with the highest concentrations measured in wells outside of the area of the contaminant plume (Figure 4.15). The maximum DO concentration of 7.03 mg/L was measured at SS003MW013 located cross-gradient to contaminant migration.

Throughout the plume, DO concentrations generally were less than 0.5 mg/L. The low concentrations of oxygen in the plume area relative to upgradient areas is a strong indication of anaerobic biological activity in the plume area. Depletion of DO within the chlorinated benzene and fuel hydrocarbon plumes indicates that microbial activity stimulated by the presence of anthropogenic hydrocarbons (e.g., benzene, chlorobenzenes, DCBs, and other fuel constituents) is depleting DO and creating anaerobic conditions. An elevated DO concentration of 1.86 mg/L was measured at monitoring well SS003MW274 in the source area. Groundwater at well SS003MW274 was not exposed to the atmosphere as the result of well drawdown during purging and the field DO meter was operational and recently calibrated. Hydrogeologic data collected to date do not indicate a cause for the relatively high DO level at this location.

4.6.1.2.2 Nitrate

Concentrations of nitrate as nitrogen (N) were measured in groundwater samples collected in March/April. Table 4.6 summarizes measured nitrate (as N) concentrations, and Figure 4.16 shows the distribution of nitrate (as N) concentrations in site groundwater. Background concentrations immediately upgradient from the plume ranged from 2.2 to 4.8 mg/L. Within the plume, nitrate concentrations were generally less than 0.5 mg/L. The area of reduced nitrate concentrations also coincides with the area of reduced DO concentrations, indicating that as DO is removed, microbes are utilizing nitrate as an electron acceptor for degradation of fuel constituents.

4.6.1.2.3 Sulfate

Sulfate concentrations were measured in groundwater samples collected in March/April 1998. Sulfate concentrations in shallow groundwater at the site ranged from <0.71 mg/L to 49.7 mg/L (Table 4.6). Figure 4-17 illustrates sulfate trends at Site S-1. Sulfate concentrations were less than 2.1 mg/L in the former sump area, and an obvious pattern exists between low sulfate concentrations and high CB and benzene concentrations. An exception to this trend was observed at monitoring well SS003MW274, where sulfate was detected at 5.8 mg/L. The average background sulfate concentration at the site is 32 mg/L. Further from the source area beneath the residential area to the north/northeast, sulfate concentrations gradually increased to between 11.2 and 15.1 mg/L. This sulfate increase is likely a result of sulfate leaching from metallic sulfides in the soil matrix or oxidation of reduced sulfite by contact with

LEGEND

Monitoring Well Location With
Dissolved Oxygen Concentration (mg/L)

Data Qualifiers
U = Analyte not detected above
associated reporting limit.
E = Estimated result. Result
concentration exceeds calibration
range.

Line of Equal Dissolved Oxygen
Concentration (mg/L),
Dashed Where Inferred

Fence

Inferred Groundwater Flow Direction

FIGURE 4.15

DISSOLVED OXYGEN
IN GROUNDWATER
(MARCH/APRIL 1998)

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado

0   100   200
Feet

LEGEND

⊕ Monitoring Well Location With
   Nitrate Concentration (µg/L)

Data Qualifiers
NA = Not Analyzed.
U = Analyte not detected above
   associated reporting limit.
E = Estimated result. Result
   concentration exceeds calibration
   range.

╱10╱ Line of Equal Nitrate Concentration
   (mg/L), Dashed Where Inferred

──×── Fence

◄ Inferred Groundwater Flow Direction
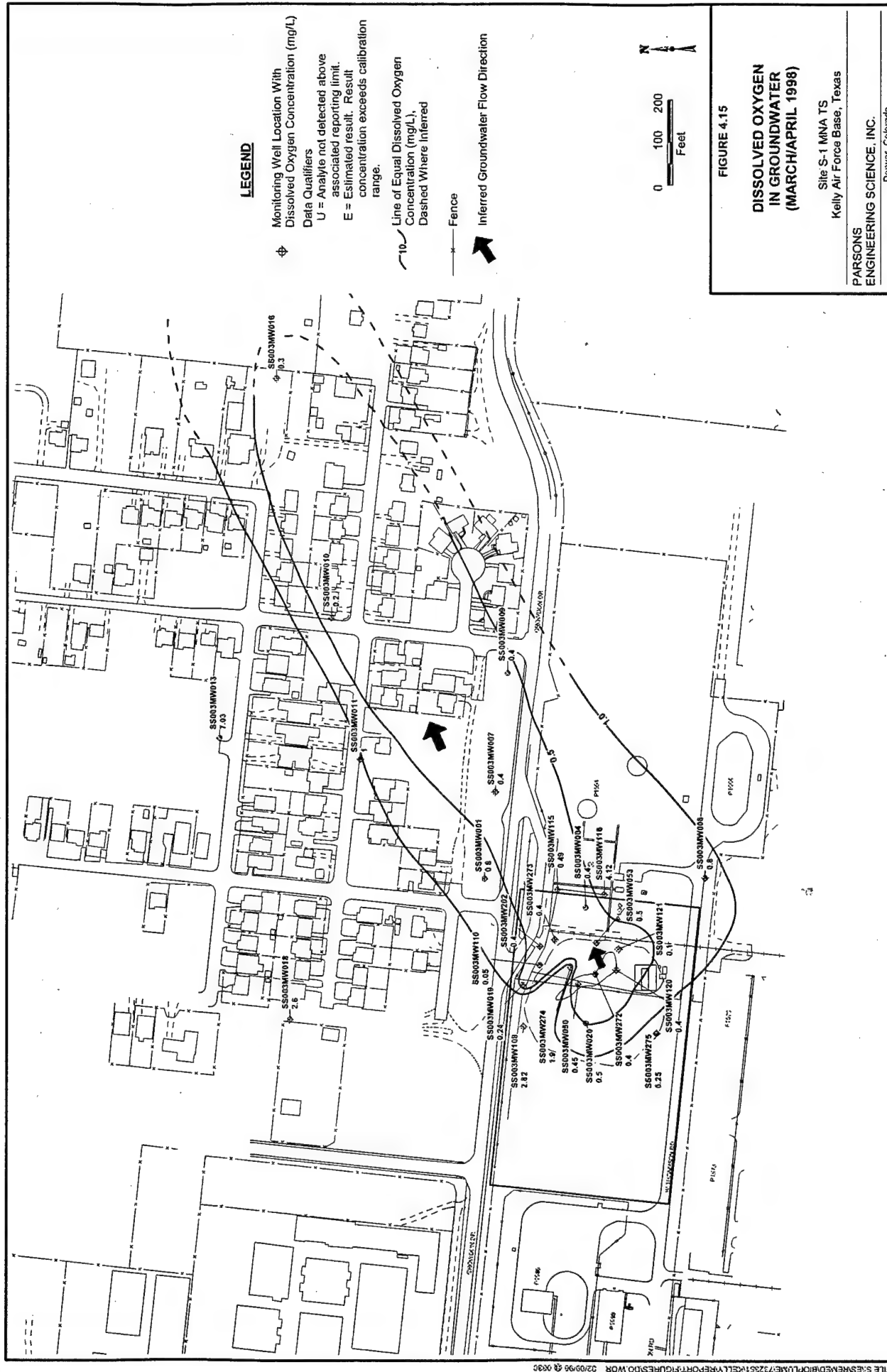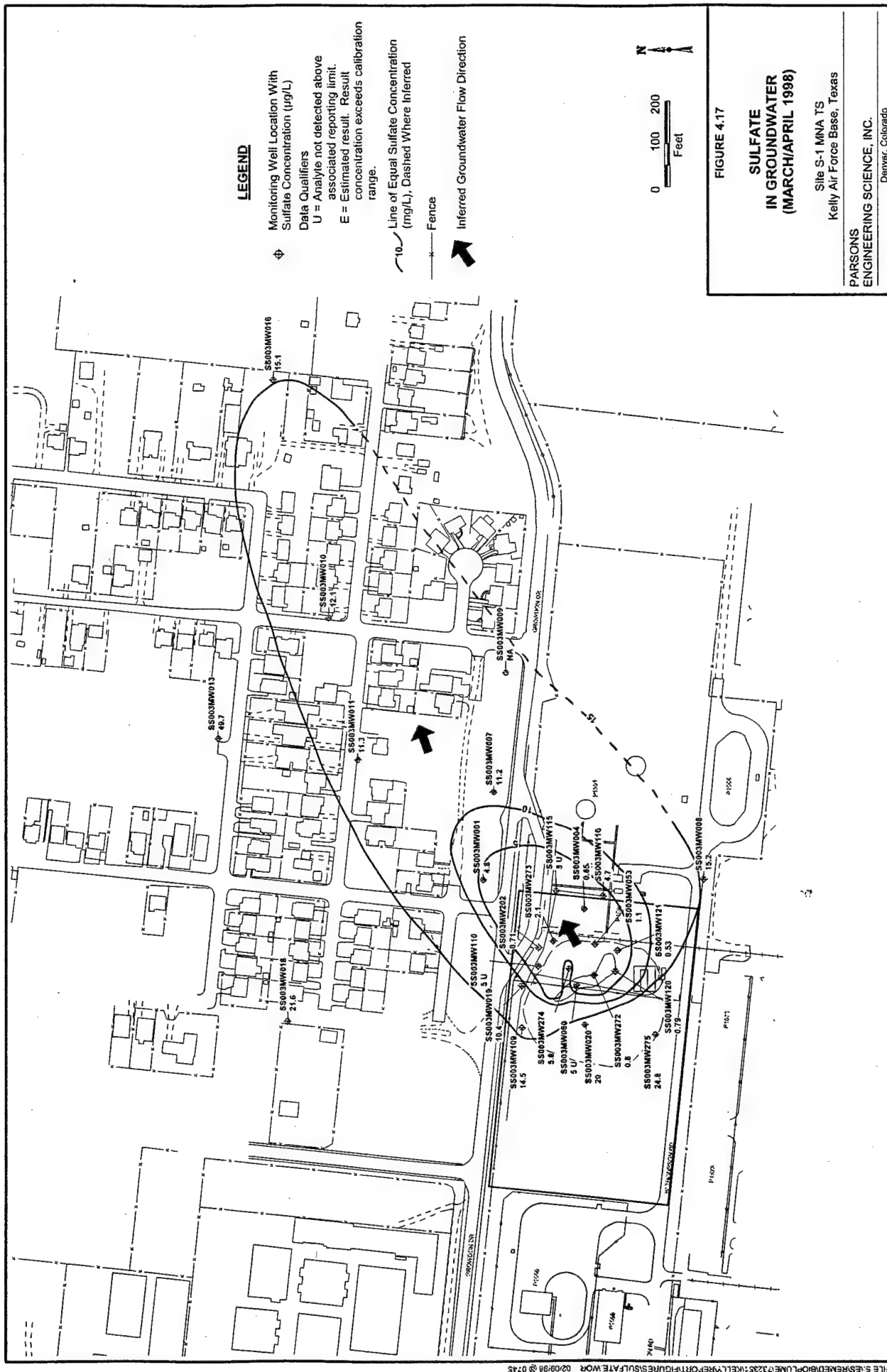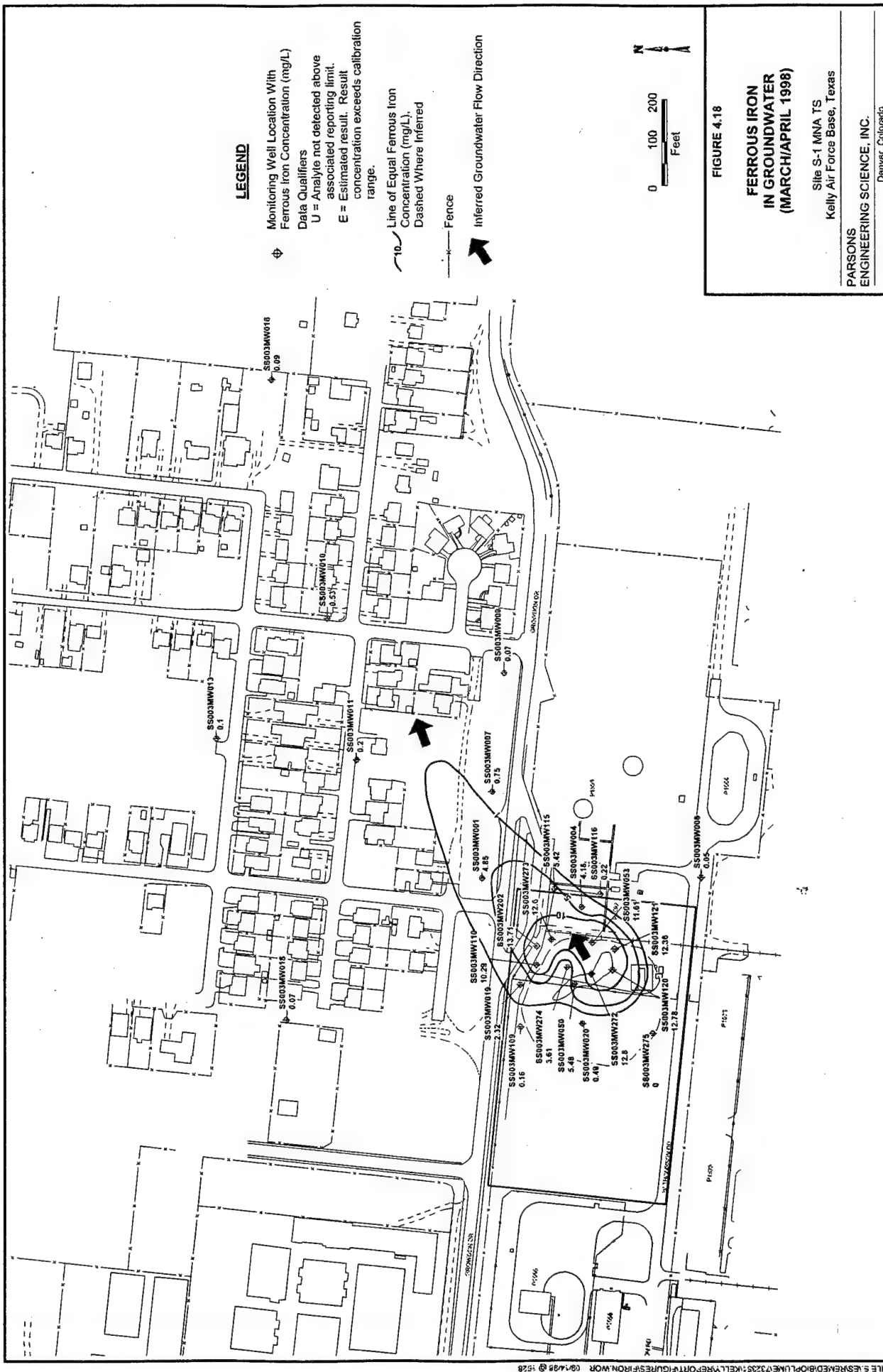
N

0   100   200
         Feet

FIGURE 4.16

**NITRATE AS NITROGEN
IN GROUNDWATER
(MARCH/APRIL 1998)**

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.

Denver, Colorado

FILE S:\ESREM\ED\BIOPLUME\73225\KELLY\REPORT\FIGURES\NITRATE.WOR   02/03/99 @ 0740

LEGEND

⊕   Monitoring Well Location With Sulfate Concentration (µg/L)

Data Qualifiers
U = Analyte not detected above associated reporting limit.
E = Estimated result. Result concentration exceeds calibration range.

╱10╱   Line of Equal Sulfate Concentration (mg/L), Dashed Where Inferred

—x—   Fence

➤   Inferred Groundwater Flow Direction

N

0   100   200
Feet

FIGURE 4.17

**SULFATE
IN GROUNDWATER
(MARCH/APRIL 1998)**

Site S-1 MNA TS
Kelly Air Force Base, Texas

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Denver, Colorado

SS003MW016
15.1

SS003MW010
12.1

SS003MW009
NA

SS003MW013
49.7

SS003MW011
11.3

SS003MW007
11.2

SS003MW001
4.5

SS003MW115
5 U

SS003MW004
0.65

SS003MW110
5 U

SS003MW053
4.7

SS003MW008
15.2

SS003MW018
21.6

SS003MW223
2.1

SS003MW202
0.71

SS003MW019
5 U

SS003MW121
1.1

SS003MW120
0.53

SS003MW109
10.4

SS003MW274
5.6

SS003MW060
5 U

SS003MW020
20

SS003MW272
0.8

SS003MW275
24.8

SS003MW108
14.5

0.79

LEGEND

⊕ Monitoring Well Location With Ferrous Iron Concentration (mg/L)

Data Qualifiers
U = Analyte not detected above associated reporting limit.
E = Estimated result. Result concentration exceeds calibration range.

Line of Equal Ferrous Iron Concentration (mg/L). Dashed Where Inferred

Fence

Inferred Groundwater Flow Direction

FIGURE 4.18

FERROUS IRON IN GROUNDWATER (MARCH/APRIL 1998)

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado

0   100   200
Feet

low levels of DO diffusing to the aquifer by cross-gradient sources, atmospheric recharged of oxygen at the groundwater/air interface, or precipitation recharge.

It is likely that sulfate reduction is an ongoing anaerobic biodegradation process at Site S-1. This is important because when a system is sufficiently reducing for sulfate reduction to occur, conditions become more favorable for reductive dehalogenation of chlorinated solvents.

4.6.1.2.4 Ferrous Iron

Ferrous iron [iron(II)] concentrations were measured in groundwater samples collected in March/April 1998. Table 4.6 summarizes ferrous iron concentrations, and Figure 4.18 shows the areal extent of ferrous iron in groundwater. Measured ferrous iron concentrations ranged from 0.0 mg/L to 13.7 mg/L. Elevated ferrous iron concentrations coincide with the solvent and hydrocarbon plumes, suggesting that ferric iron hydroxide [iron(III)] is being reduced to ferrous iron during biodegradation of native organic carbon and BTEX. Background levels of ferrous iron average approximately 0.03 mg/L, as measured at upgradient wells (e.g., SS003MW008 & SS003MW275). The maximum ferrous iron concentrations (>10.0 mg/L) were detected in the vicinity of, or downgradient from, the source area in the former sump. Sporadic ferrous iron detections along the centerline and downgradient from the former sump area (e.g., wells SS003MW001, -010, and -016) are within anaerobic portions of the plume and it is feasible that limited iron reduction is occurring at these locations. The disappearance of high ferrous iron concentrations beyond the source area is due to a combination of the following: 1) partial dilution by dispersion; and 2) oxidation to ferric hydroxide ($FeOH_3$) or other iron complexes (e.g., FeS_2 and $FeCO_3$) as a result of major changes in groundwater redox potentials and minor changes in pH from the source area (Hem, 1984).

Recent evidence suggests that the reduction of ferric iron to ferrous iron cannot proceed at all without microbial mediation (Lovley and Phillips, 1988; Lovley et al., 1991; Chapelle, 1993). None of the common organic compounds found in low-temperature (i.e., non-hydrothermal), neutral, reducing groundwater could reduce ferric oxyhydroxides to ferrous iron under sterile laboratory conditions (Lovley et al., 1991). This means that the reduction of ferric iron requires microbial mediation by microorganisms with the appropriate enzymatic capabilities. Because the reduction of ferric iron cannot proceed without microbial intervention, the elevated concentrations of ferrous iron that were measured in the contaminated groundwater at the site are very strong indicators of microbial activity.

4.6.1.2.5 Methane

Methane concentrations were measured in groundwater samples collected in March/April 1998. Table 4.6 lists methane concentrations, which ranged from 0.2 mg/L to 5.7 mg/L at the site. Figure 4.19 shows the distribution of methane in shallow site groundwater. The area of elevated methane concentrations correlates well with the chlorinated benzene and benzene/toluene plumes. The presence of methane in the plume area indicates that conditions are sufficiently reducing for petroleum hydrocarbons and native organic matter to be used to support methanogenesis. Furthermore, the fact that methanogenesis is ongoing indicates that conditions in the

LEGEND

⊕ Monitoring Well Location With Methane Concentration (mg/L)

Data Qualifiers
 U = Analyte not detected above associated reporting limit.
 E = Estimated result. Result concentration exceeds calibration range.

⌐10⌐ Line of Equal Methane Concentration (µg/L), Dashed Where Inferred

—×— Fence

➤ Inferred Groundwater Flow Direction
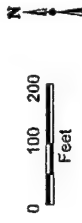
FIGURE 4.19

**METHANE
IN GROUNDWATER
(MARCH/APRIL 1998)**

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.

Denver, Colorado

0   100   200
Feet

plume area are strongly reducing, and therefore are favorable for reductive dehalogenation of chlorinated solvents.

The gradual disappearance of methane from groundwater at Site S-1 is most likely due to volatilization, especially considering the high volatility of methane and the relative thinness of the aquifer in the source area. Methane is readily biodegradable to CO_2 and water under aerobic or mildly aerobic (e.g., nitrate reducing) conditions, but is not degradable under highly anaerobic, reducing conditions. DO concentrations that coincide with the methane plume are below 0.5 mg/L and aerobic oxidation of methane, once formed by the transformation of natural organic carbon and contaminants, is not likely at Site S-1.

4.6.1.3 Ethane/Ethene in Groundwater

Ethene and ethane are the ultimate end products of the reductive dehalogenation of PCE, TCE, TCA, and DCA. Most chlorinated ethene detections occurred outside of the Site S-1 CB plume to the southeast (i.e., SS003MW008) and to the north (i.e., SS003MW018, SS003MW013). Concentrations of ethane and/or ethene less than 0.006 mg/L primarily were detected from the former sump area. Table 4.6 lists detected ethene and ethane concentrations. The lack of ethene and ethane at locations where chlorinated ethene concentrations have been relatively high coincides with the presence of aerobic groundwater conditions that inhibit reductive dechlorination. On the other hand, the presence of low levels of ethene and ethane at Site S-1 confirm that low levels of chlorinated ethenes or ethanes have been present in the former sump area.

4.6.2 Additional Geochemical Indicators

Other geochemical data collected for this evaluation can be used to further interpret and support the contaminant, electron donor, electron acceptor, and byproduct data previously discussed. These parameters provide additional qualitative indications of what biodegradation processes may be operating at the site.

4.6.2.1 Oxidation/Reduction Potential As An Indicator of Redox Processes

ORPs were measured at groundwater monitoring wells as part of this study. ORP is a measure of the relative tendency of a solution to accept or transfer electrons. The ORP of a groundwater system depends on which electron acceptors are being reduced by microbes during oxidation of organic compounds. ORPs for shallow groundwater at the site ranged from 286 millivolts (mV) to -228 mV. Table 4.7 summarizes available ORP data, and Figure 4.20 illustrates ORP trends. High ORPs generally were detected upgradient and crossgradient from the contaminant plume. Low ORPs (<0 mV) coincide with the head of the groundwater plume located at the former sump area. ORP values begin to increase above 0 mV downgradient from monitoring well SS003MW001, but remain below 100 mV for up to 800 additional feet. As expected, ORP trends generally are consistent with the contaminant source, the shape of the CB plume, and evidence of ongoing reductive dechlorination; decreased DO, nitrate, sulfate concentrations; and elevated ferrous iron and methane concentrations. Relatively low DO and sulfate concentrations persist at monitoring wells SS003MW010 and SS003MW016, whereas redox conditions have increased above 100 mV. High redox conditions at locations with mildly depleted electron acceptors (e.g., DO and
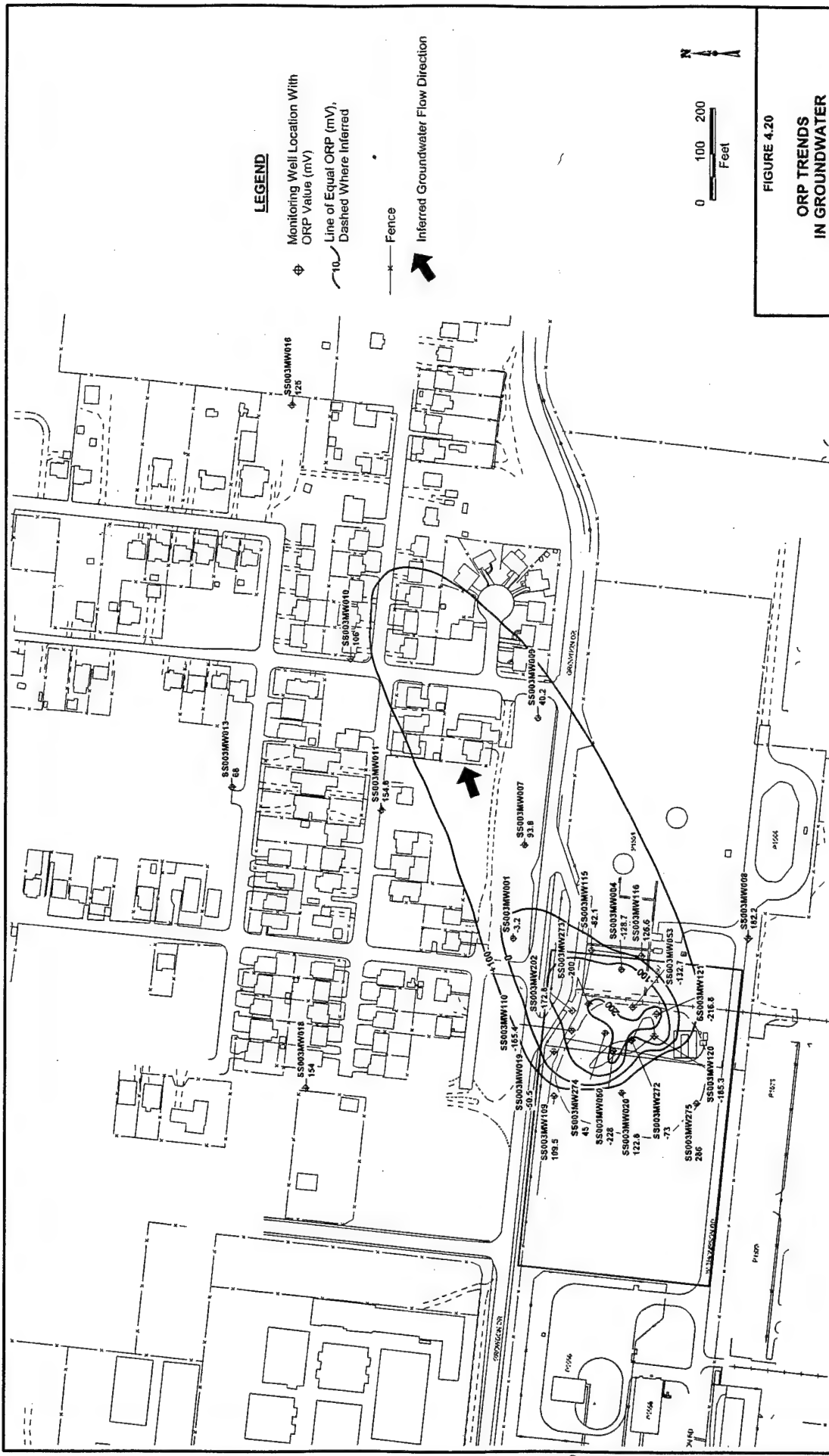
LEGEND

Monitoring Well Location With
ORP Value (mV)

Line of Equal ORP (mV),
Dashed Where Inferred

Fence

Inferred Groundwater Flow Direction

sulfate at wells SS003MW010 and SS003MW016) are not uncommon at sites, as many authors have noted that field redox potential data cannot be used to reliably predict all the electron accepting processes that may be operating at a site, because the platinum electrode probes are not sensitive to some redox couples (e.g., sulfate/sulfide) (Stumm and Morgan, 1981; Godsey, 1994; and Lovley et al., 1994). Furthermore, low DO conditions do not necessarily indicate low redox conditions within an aquifer because numerous other redox reactions are possible that can affect the redox equilibrium of groundwater, although deoxygenation is the most common (Hounslow, 1995).

4.5.2.2 Carbon Dioxide Evolution and Groundwater Alkalinity

Carbon dioxide is produced during the biodegradation of anthropogenic and native organic carbon compounds. Carbon dioxide forms carbonic acid that dissolves carbonate minerals where present in the aquifer matrix, thereby increasing the alkalinity of the groundwater. An increase in alkalinity [measured as calcium carbonate ($CaCO_3$)] in an area with BTEX compounds or chlorinated solvent (particularly less-chlorinated solvents) concentrations elevated above background conditions can be used to infer that petroleum hydrocarbons, less-chlorinated solvents, or native organic carbon have been consumed through aerobic and anaerobic microbial respiration.

Measurements of free carbon dioxide in March/April 1998 (Table 4.7) indicate that carbon dioxide was being produced at Site S-1. As shown on Figure 4.21, carbon dioxide concentrations at the head and along the centerline of the plume are noticeably elevated above background concentrations. Background concentrations are about 52 to 100 mg/L, while concentrations within the CB plume range from 100 to 160 mg/L. Carbon dioxide concentrations above background result from both aerobic and anaerobic biodegradation processes as contaminants are ultimately converted to carbon dioxide and water.

The production of carbon dioxide would suggest corresponding changes in total alkalinity as a result of microbial activity. Total alkalinity (as $CaCO_3$) was measured in groundwater samples collected in March/April 1998 to confirm this trend. These measurements are summarized in Table 4.7 and shown of Figure 4.22. Total alkalinity at the site varied from 215 mg/L to 605 mg/L. This range of alkalinity is sufficient to buffer potential changes in pH caused by biologically mediated reactions and suggests that aerobic and/or anaerobic biodegradation processes should not cause detrimental shifts in groundwater pH (see Section 4.6.2.3). In addition, the areas with increased alkalinity coincide with the chlorinated benzene and fuel hydrocarbon plumes. This is further evidence that biodegradation utilizing fuel hydrocarbons and native organic carbon compounds as substrates is ongoing at the site.

4.6.2.3 pH

pH was measured for groundwater samples collected from monitoring points and monitoring wells in March/April 1998 (Table 4.7). The pH of a solution is the negative logarithm of the hydrogen ion concentration [H^+]. The groundwater pH measured at the site ranged from 6.4 to 8.7 standard units, The highest pH of 8.7 standard units measured at SS003MW053 was anomalous in that the next highest groundwater pH was 7.2 standard units. The range of pH measured at the site is within an acceptable range for fuel-degrading microbes. The limited and relatively neutral
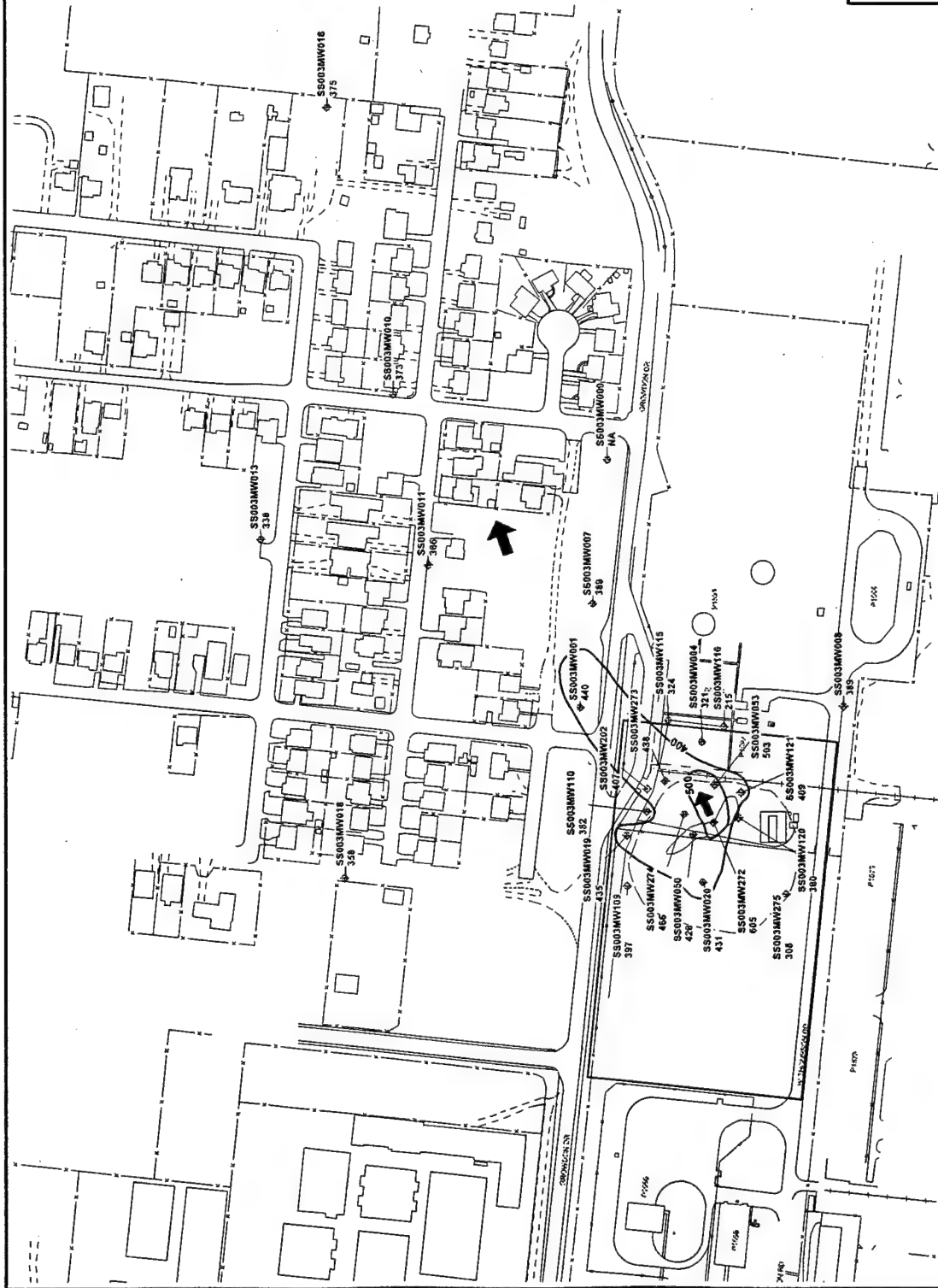
LEGEND

⊕ Monitoring Well Location With Carbon Dioxide Concentration (mg/L)

Data Qualifiers
U = Analyte not detected above associated reporting limit.
E = Estimated result. Result concentration exceeds calibration range.

/10/ Line of Equal Carbon Dioxide Concentration (mg/L). Dashed Where Inferred

—x— Fence

Inferred Groundwater Flow Direction

FIGURE 4.21

CARBON DIOXIDE IN GROUNDWATER (MARCH/APRIL 1998)

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.

Denver, Colorado

0   100   200
Feet

LEGEND

⊕ Monitoring Well Location With Alkalinity
as CaCO3 Concentration (mg/L)

Data Qualifiers
U = Analyte not detected above
associated reporting limit.
E = Estimated result. Result
concentration exceeds calibration
range.

⌒10⌒ Line of Equal Alkalinity
Concentration (mg/L).
Dashed Where Inferred

—×— Fence

↗ Inferred Groundwater Flow Direction

FIGURE 4.22

ALKALINITY
IN GROUNDWATER
(MARCH/APRIL 1998)

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.

Denver, Colorado

0   100   200
Feet

N

range of pHs also indicates that microbial reactions have minimal effect on groundwater pH, likely due to the moderately high alkalinity of site groundwater (Section 4.6.2.2).

4.6.2.4 Temperature

Groundwater temperature was measured at groundwater monitoring points and monitoring wells in March/April 1998. Table 4.7 summarizes groundwater temperature readings. Temperature can affect the types and growth rates of bacteria that can be supported in the groundwater environment, with higher temperatures typically resulting in higher growth rates. Groundwater temperatures at Site S-1 varied from 21.7 degrees Celsius (°C) to 26.2°C. These are relatively warm temperatures for groundwater (but still within the optimal range), suggesting that bacterial growth rates should be high.

4.7 ESTIMATION OF BIODEGRADATION RATES

Biodegradation rate constants are necessary to accurately simulate the fate and transport of contaminants dissolved in groundwater. In many cases, biodegradation of contaminants can be approximated using first-order kinetics. First-order biodegradation rate constants may be calculated on the basis of field-scale data, or by using a small sample of the aquifer material and groundwater for microcosm studies.

For reductive dehalogenation of chlorinated compounds, first-order rates are not necessarily an accurate representation because the degradation of TCB or DCB depends on both the concentrations of electron donors (e.g., fuel hydrocarbons or native organic material) and the concentrations of electron acceptors (including inorganic acceptors and TCB and/or DCB). Second-order rates would therefore allow more accurate modeling, but at this time there are no readily available groundwater contaminant transport models that can utilize such rates (Moutoux *et al.*, 1996). Therefore, first-order rates must be estimated for such an application.

Microcosm studies are useful for demonstrating that the microorganisms necessary for biodegradation are present and to help quantify rates of biodegradation. Because literature supporting chlorinated benzene biodegradation in the environment is limited, microcosm studies were performed for Site S-1 to confirm that observed losses of chlorinated benzenes was partially biological and to provide estimated biodegradation rates for aerobic CB oxidation and TCB and DCB dechlorination (see Section 4.8). Relatively little is published in scientific literature regarding these biodegradation processes and rates, and therefore, microcosm studies at Site S-1 were deemed appropriate to add to the base of scientific knowledge necessary to lend support to observed natural attenuation trends for chlorinated benzenes at Site S-1.

Although microcosm studies can provide useful biodegradation mechanism and rate information, microcosms are invariably influenced by the nature of the geological material submitted for study, the physical properties of the microcosm, the sampling strategy, and the duration of the study. Biodegradation rate constants determined by microcosm studies often are much higher than those observed in the field. Microcosm results are useful indicators of the potential for natural bioremediation, and can demonstrate that contaminant losses are biological, but it may not be appropriate to use them to generate rate constants. The preferable method of contaminant biodegradation rate-constant determination is by use of field data.

TABLE 4.8

SUMMARY OF ESTIMATED BIODEGRADATION RATES

SITE S-1 MNA TS

KELLY AFB, TEXAS

Analysis Method	Process	Dechlorination Sequence	Estimated Migration Pathway	Sampling Date	Decay Rate (day^{-1})	Half Life (days)
Downgradient of Source Area						
B&A[a]	CB Biodegradation	Not Applicable	SS003MW001 to SS03MW010 to SS003MW016	July/August 1989	8.6×10^{-4}	805
B&A	CB Biodegradation	Not Applicable	SS003MW001 to SS03MW010 to SS003MW016	October 1990	7.9×10^{-4}	877
B&A	CB Biodegradation	Not Applicable	SS003MW001 to SS03MW010 to SS003MW016	December 1995	1.2×10^{-3}	578
B&A	CB Biodegradation	Not Applicable	SS003MW001 to SS03MW010 to SS003MW016	March/April 1998	7.9×10^{-4}	877
B&A	CB Biodegradation	Not Applicable	SS003MW001 to SS03MW010 to SS003MW016	June 1998	2.2×10^{-3}	315
Source Area						
B&A	CB Biodegradation	Not Applicable	SS003MW272 to SS003MW273	March/April 1998	1.43×10^{-2}	48
B&A	CB Biodegradation	Not Applicable	SS003MW202 to SS003MW001	March/April 1998	1.9×10^{-2}	36
B&A	CB Biodegradation	Not Applicable	SS003MW115 to SS003MW007	March/April 1998	1.62×10^{-2}	43
B&A	Total DCB Dechlorination	DCB to CB	SS003MW272 to SS003MW273	March/April 1998	6.74×10^{-2}	10
Reductive Dechlorination[b]	Total DCB Dechlorination	DCB to CB	SS003MW272 to SS003MW273	March/April 1998	4.6×10^{-3}	151

a/ B&A = Method of Buscheck and Alcantar (1995) for steady-state plumes.

b/ Reductive Dechlorination = Method of Moutoux *et al.* (1996), which gives decay rate attributable to reductive dechlorination.

Note: The average total organic carbon content of soils was assumed to be 0.0005 mg/kg (literature value) and the effective porosity 0.3 for retardation rates used in the calculation of biodegradation rates (see Appendix D).

In order to calculate first-order biodegradation rate constants on the field scale, the apparent degradation rate must be normalized for the effects of dilution, dispersion, and sorption. One method proposed by Buscheck and Alcantar (1995) involves interpretation of a steady-state contaminant plume and is based on the one-dimensional, steady-state analytical solution to the advection-dispersion equation presented by Bear (1979). This method can be adapted to estimate rate constants for chlorinated benzenes. Another method for estimating dehalogenation rates for CAHs and chlorinated benzenes is described by Moutoux et al. (1996). This method provides a total dechlorination rate for all dechlorination steps. All rates are averaged together using the Moutoux et al. (1996) method.

Estimated field biodegradation rates for CB should be evaluated with the knowledge that CB biodegradation primarily is dependent on the rate of oxygen supply to the aquifer. The ability for CB to be directly oxidized under anaerobic, reducing conditions has not been sufficiently studied and biodegradation processes responsible for benzene biodegradation under anaerobic conditions (e.g., nitrate reduction, iron reduction, sulfate reduction, and methanogenesis) have not been documented to similarly transform CB. Therefore, estimated biodegradation rates for CB may be singularly affected by oxygen availability. Biodegradation rates measured at the head of the groundwater plume at Site S-1 may be higher as a result of direct oxygen recharge from upgradient groundwater than rates measured further downgradient where oxygen concentrations are uniformly depleted. Oxygen recharge to the plume core area at downgradient locations is probably slower and limited to diffusion from peripheral oxygenated waters and from precipitation recharge.

Previous macrocosm studies performed at Site S-1 indicated that the indigenous consortia of CB-degrading microorganisms were able to achieve optimum biodegradation rates within a period of 7 days after being exposed to excess oxygen and increasing levels of CB vapor (Nishino et al., 1994). This further suggests that biodegradation rates for CB at the site are oxygen limited and macrocosm study rates are not. The estimated residence time for contamination at Site S-1 is at least 7.5 years (defined as the time needed to travel from the source area to near the leading edge of the plume), which is much longer than is needed for microorganisms to degrade CB when oxygen is present. Therefore, the term "field-biodegradation rates" is to be used to differentiate between microbial biodegradation rates at the microscopic level, and field-biodegradation rates which serve to more accurately describe contaminant loss on a site-wide scale.

The Buscheck and Alcantar (1995) and Moutoux et al. (1996) methods were used to estimate first-order, field-biodegradation rate constants for chlorinated benzenes at Site S-1. The methods and results are summarized in Table 4.8. The calculation spreadsheets used to estimate these rates are provided in Appendix D. Historic CB concentrations were used to assess potential changes in field-biodegradation rates over a period of nine years from July/August 1989 to June 1998. Monitoring wells SS003MW001, SS003MW010, and SS003MW016 were assumed to represent the pathline of contaminant migration at Site S-1 beyond the source area. Groundwater velocities along this pathline have been relatively constant over the measured history of the site, resulting in better resolution of historic field-biodegradation rates because the method of Buscheck and Alcantar (1995) and the Moutoux et al. (1996) are sensitive to variations in groundwater velocity. CB field-biodegradation rates calculated for the specified pathline ranged from 7.9×10^{-4} to 2.2×10^{-3} day^{-1}. Field-biodegradation rates for CB in the source

area ranged from 1.43×10^{-2} to 1.9×10^{-2} day^{-1}; these rates were calculated using data from the pathlines listed in Table 4.8. The recharge of oxygenated groundwater into the source area from upgradient likely resulted in the order-of-magnitude increase in field-biodegradation rates between the source area and the downgradient pathline. The DCB field-dechlorination rate computed using March/April 1998 data from Site S-1 and the Buscheck and Alcantar (1995) method was 6.74×10^{-2} day^{-1} for total DCBs to CB. Decay rates computed using the Moutoux *et al.* (1996) method for DCB to CB indicated a reductive dechlorination rate of 4.6×10^{-3} day^{-1}. Although the majority of DCB likely is converted to CB through reductive dechlorination, a partial loss of DCB may be occurring through aerobic oxidation where the source area is prone to oxygenation near the upgradient edge of the contaminant plume. This effect may contribute to rapid DCB losses at Site S-1.

4.8 MICROCOSM STUDY RESULTS

4.8.1 Anaerobic Microcosm Study Results

The materials collected at Kelly AFB were placed in glass microcosms designed to allow the periodic measurement of CB concentrations under an anaerobic atmosphere. It was soon determined that the soils used for the anaerobic microcosms study were compromised by excessively high LNAPL volumes intermixed within the soil matrix. The effect of the LNAPL was to provide a sink that immediately absorbed the CB added to the microcosm. As a result, the combined effects of contaminant biodegradation versus contaminant dissolution into the LNAPL could not be distinguished. Biodegradation rate kinetics were masked by the immediate dissolution of injected CB and/or DCB concentrations into the LNAPL and anaerobic microcosm study results for Site S-1 are inconclusive.

4.8.2 Aerobic Microcosm Study Results

4.8.2.1 Aerobic Microcosm Study Methods

Aquifer solids collected from soil boring SS003SB280 and approximately 1 gallon of water collected from nearby well SS003MW010 (approximately 80 feet to the east) were combined to create the microcosm matrix. The location of SS003SB280 was near the mid-northern portion of the groundwater plume and within the observed 10 µg/L chlorobenzene contour (Figures 2.1 and 4.9). The CB concentration in well SS003MW010 was 45 µg/L at the time of sampling. Washed Ottawa sand was placed in a 25 millimeter (mm) by 15 centimeter (cm) glass column to a height of 1 cm. The silt, sand and gravel from the soil boring was layered an additional 6 cm over the Ottawa sand. The remaining 8 cm was packed with additional Ottawa sand. Filter-sterilized (0.22 micron [µ]) groundwater was sparged with oxygen and the CB content adjusted to bring the concentration to 7.3 mg/L to serve as the feed reservoir. The influent was delivered to the bottom of the column via a peristaltic pump and drained through an overflow at the top of the column. The pore volume of the microcosm was 38 cubic centimeter (cm^3). All tubing connected to the column was Viton or stainless steel. Influent feed water was sampled at the pump, whereas effluent waters were sampled at various pumped volumes from the microcosm. For the first seven days the column was flushed daily with 150 ml of feed delivered over a 60-minute period.

Small static microcosms were set up with the same materials used in the column described above. The heavy particulates were allowed to settle in unfiltered groundwater. The top layer containing suspended fine particles was decanted off, sparged with oxygen, and the chlorobenzene content adjusted to 5 mg/L. Two milliliters were aseptically pipetted into each of 40 sterile 2-mL amber vials with sterile screw caps and Teflon®-lined septa. Half of the vials had 5 µl of HgCl$_2$ (60 milligrams per milliliter [mg/ml]) added to create abiotic controls. The vials were sealed and stored inverted at room temperature. When left undisturbed, the fine particulates settled out of the water column. The vials were inverted daily to resuspend the particulates. The vials were sacrificed at determined intervals for analysis of CB concentrations.

CB was analyzed with a Hewlett Packard high performance liquid chromatograph (HPLC) with a model 1040M diode array detector. CB was separated on a Hypercarb (3 mm x 100 mm) porous graphite column with a mobile phase of acetonitrile and water (70:30) monitored at 210 nanometers (nm). The flow rate was 1 mL/min.

4.8.1.3 Aerobic Microcosm Study Results and Discussion

4.8.1.3.1 Column Study

In the first 2 days of operation of the column, there was little difference between CB concentrations in the influent and various pumped effluent volumes (Table 4.9). However after 3 days, the concentration of CB in the effluent sample taken at 20 ml was much lower than that in the influent and in the effluent sample taken at 120 mL (nominal 3 column volumes). After 7 days the intermittent mode was terminated and feed was pumped in continuously (Table 4.10). Once continuous flow was initiated, CB degradation became increasingly rapid. The results indicate that chlorobenzene-degrading bacteria were viable in the subsurface materials and that the acclimation period was 3 days for establishment of substantial CB biodegradation rates. CB degradation appears to be caused by induction of a pre-existing CB degradative microbial population and not the result of a new genetic recombination as indicated by the short time required for CB degradation to begin (Nishino *et al.*, 1994).

4.8.1.3.2 Serum Vial Study

The sealed vials containing unfiltered groundwater showed no change in CB concentration for the first 7 days (Table 4.11). Thereafter, samples were analyzed once a week. Half the CB was gone from both untreated and mercury treated vials after 2 weeks, and completely gone from 38% of the untreated vials after 3 weeks. A small residual amount remained in all the abiotic controls and 62% of the untreated vials at 3 weeks. There was no difference in the concentration of CB between treated and untreated vials (excluding vials with no CB remaining) at the 95% confidence level (Table 4.12). However, complete removal of CB from some of the untreated vials may be evidence of a low level of CB degradation. If it is assumed that a single CB-degrading bacterium is capable of induction and growth on CB and that complete removal of CB from an untreated vial represents the presence of 1 or more CB-degrading bacteria in the water sample, then the result that 62% of the untreated vials were not different from the mercury treated vials suggests that groundwater with fine particulates contains on average less than one CB-degrading bacterium per mL. Each of the remaining 38% of the vials contained at least one bacterium able to degrade CB.

TABLE 4.9
CHLOROBENZENE IN VARIOUS PUMPED VOLUMES OF THE SOIL COLUMN OPERATED IN INTERMITTANT MODE
SITE S-1 MNA TS
KELLY AFB, TEXAS

Days of Operation	Chlorobenzene in Feed Water (mg/L)	Chlorobenzene at 20 mL Pumped Effluent Volume (mg/L)	Chlorobenzene at 120 mL Pumped Effluent Volume (mg/L)
0	7.3	7.9	6.9
1	7.3	6.2	6.5
3	7.4	3.1	5.6
5	5.8	1.7	4.7
6	5.5	1.2	5.0
7	5.6	0.7	4.7

TABLE 4.10
CHLOROBENZENE IN SOIL COLUMN EFFLUENT DURING CONTINUOUS FEEDING
SITE S-1 MNA TS
KELLY AFB, TEXAS

Flow rate (mL/hour)	Hours of operation at specified flow rate	Chlorobenzene (mg/L) in Effluent[a]
35	0.5	0.7
35	14.5	0.0
40	1	0.0
75	1	0.0
130	1	1.6
130	1.5	1.2
200	2.0	2.0
200	2.5	1.1

[a] Chlorobenzene in influent = 5.5 mg/L.

TABLE 4.11
CHLOROBENZENE IN SEALED VIALS
SITE S-1 MNA TS
KELLY AF B, TEXAS

Days Incubation	Killed Control	Experimental
0	6.10	7.40
0	7.20	6.90
0	7.40	6.80
1	6.50	6.80
2	6.90	6.30
4	6.50	6.10
7	6.10	5.70
15	2.32	2.07
15	2.23	2.15
15	2.36	1.98
22	0.85	0.00
22	0.94	0.81
22	0.83	0.00
22	1.02	0.91
22	0.81	0.84
22	0.51	0.68
22	0.63	0.71
22	0.86	0.00

TABLE 4.12
MEAN AND 95% CONFIDENCE LIMIT OF CHLOROBENZENE
IN SEALED VIALS
SITE S-1 MNA TS
KELLY AF B, TEXAS

Days Incubation	Killed Control	Experimental
0	6.90 ± 1.28	7.03 ± 0.59
15	2.30 ± 0.13	2.07 ± 0.16
22	0.81 ± 0.13	0.79 ± 0.11

Note: Non-zero vials only.

The result that the amount of CB remaining in vials at 22 days did not distinguish between abiotic controls and untreated samples suggests that there was also a significant and steady abiotic loss of CB from the vials. A possible source of loss is slow absorption onto the septa.

The aerobic microcosm study results indicate that the aquifer solids harbor a CB-degrading population able to respond to the reintroduction of CB within a short period. The longer lag time in vials before significant CB disappearance occurred can be interpreted as the time required for a very small population of CB-degrading bacteria to grow enough to make an impact on the CB available to them (Spain, 1990). It is unlikely that the CB degradation response was the result of genetic events. Laboratory evolution of CB-degradation pathways have involved selection times of 6 to 14 months (de Bont *et al.*, 1986; Haigler *et al.*, 1988; Reineke & Knackmuss, 1984; Schraa *et al.*, 1986; Spain & Nishino, 1987; Van der Meer, 1987). No predictions can be made about the long-term survival of the CB-degrading trait in the formerly contaminated soil and groundwater at Kelly AFB, but it is apparent that at the fringes of the plume a significant CB-degrading population exists and can acclimate rapidly to degrade CB. The results in Tables 4.9 through 4.11 indicate a substantial capacity for CB degradation and suggest that the rate might only be limited by the mass transfer of CB and the availability of oxygen.

4.9 DISCUSSION

Groundwater contaminant trends and geochemical indicator data were analyzed for evidence that would satisfy several report objectives outlined in Section 1. The purpose of these analytes was to determine if natural attenuation is reducing contaminant concentrations at Site S-1 and to identify which chemicals were susceptible to natural biological attenuation (i.e., biodegradation). Furthermore, the purpose of this study, and particularly the focus of Section 4, was to identify which biological mechanisms were responsible for large-scale contaminant reductions and to attempt to approximate rates of biodegradation.

Several VOCs and SVOCs were identified during this study that have also been detected in previous groundwater sampling events. Chlorinated benzenes are of primary interest at Site S-1 because they are present at the highest concentrations and over the largest area. Other fuel hydrocarbon contaminants were identified in site groundwater, in particular benzene and naphthalene. Fuel hydrocarbons such as these are highly susceptible to aerobic and anaerobic biodegradation, and are only present at relatively low concentration in both source LNAPL and groundwater at Site S-1. For this reason, fuel hydrocarbons are not the primary contaminants of concern under current land use scenarios. Furthermore, fuel hydrocarbons promote the depletion of groundwater DO concentrations which is beneficial for natural dechlorination processes.

Chlorinated solvents in the form of PCE, TCE and DCE were detected at higher concentrations outside of the CB plume than in the Site S-1 source area. Chlorinated ethene contamination is emanating from alternate sites to the northwest and southeast of Site S-1; evaluation of these sources is not within the scope of this project. Chlorinated ethene concentrations at Site S-1 are several orders of magnitude lower than measured CB concentrations, and are susceptible to transformation to less-chlorinated intermediates (e.g., vinyl chloride), especially in the highly reducing environment present at Site S-1. The highest detected chlorinated ethene concentration migrating from Site S-1 was 5.9

μg/L of *cis*-1,2-DCE at monitoring well SS003MW001. The prevalence of the *cis* isomer as opposed to the *trans* isomer suggests that this compound was formed during the reductive dechlorination of TCE.

The first objective of this report was to estimate the effect of aerobic biodegradation in reducing CB contamination at Site S-1 (see Section 1). The following paragraphs summarize project results relating to this objective:

- Historic groundwater data was reviewed together with the current analytical data set to provide indications of CB plume stability over the past 9 years (1989 to 1998). CB declines in downgradient wells in recent years suggest that the CB plume at Site S-1 significantly has been diminished in size compared to the 1989 plume.

- DO concentrations measured in March/April 1998 indicate that the groundwater plume is mostly anaerobic and that DO concentrations were less than 0.5 mg/L throughout most of the shallow aquifer at Site S-1. Peripheral groundwater DO concentrations were as high as 7.03 mg/L north of the CB plume. Because background DO concentrations are relatively high (at least 6.25 mg/L), a significant amount of CB and other dissolved contaminant are biodegraded before the DO is depleted in the source area. The anaerobic conditions of the CB plume allows CB that migrates from the source area to persist. Biodegradation of downgradient CB must either result from reoxygenation through rainfall infiltration, oxygen diffusion through the groundwater/air interface, or through dispersion of DO into the plume from surrounding groundwater.

- Aerobic field-biodegradation rates at over the entirety of the CB plume ranged from 7.9×10^{-4} day^{-1} to 1.9×10^{-2} day^{-1} (half-lives of 877 to 36 days), respectively. Field-biodegradation rates for CB at off base locations (northeast of the base perimeter and well SS003MW001) range from 1.2×10 to 2.2×10 (half-lives of 877 to 315 days, respectively).

- Aerobic microcosm data indicate that a viable population of CB-degrading microorganisms exists at site S-1. Rapid biodegradation rates were achieved in flow-through microcosm studies in as little as three days. This short lag time indicated that the CB-degrading microbes were already present at the site, although at low population levels, and were not the result of genetic recombination by the microbial degradation of similarly structured contaminants (e.g., benzene and toluene). This results of the microcosm study suggest that the groundwater aquifer will retain the microorganisms needed to aerobically biodegrade CB, even after periods of plume recession.

The second objective of the report was to estimate the effect of anaerobic biodegradation in reducing concentrations of TCB, DCB, and CB at Site S-1 (see Section 1). The following paragraphs summarize project results relating to this objective:

- TCB and DCB compounds are present in Site S-1 media and were identified in LNAPL sources as part of this study. However, TCB is not a major contaminant and was detected at only two monitoring wells in the source area at concentrations less than 24 μg/L. All three isomers of DCB were measured at numerous wells in

the source area. However, DCB rapidly disappears downgradient from the source area and does not appear to migrate past monitoring well SS003MW001.

- Chemical and geochemical evidence indicates that TCB and DCB at Site S-1 are being biodegraded, either aerobically as substrates or anaerobically as electron acceptors. Geochemical data indicate that DO, nitrate, and sulfate are being consumed, and iron (II) methane, and chloride are being produced within the dissolved plume. These data strongly indicate that microbial consumption of anthropogenic and natural organic matter (carbon compounds) is taking place at Site S-1. Anthropogenic carbon compounds that can act as substrates are present as petroleum hydrocarbons and less-chlorinated solvents (including, but not limited to, BTEX, naphthalene, DCB, CB, VC, and DCE) dissolved in groundwater. Native carbon compounds include solid organic matter in the aquifer matrix and whatever portion of that matter that has dissolved into site groundwater. These compounds can serve as electron donors in redox reactions that also are consuming electron acceptors (e.g., DO, ferric iron, carbon dioxide, and chlorinated hydrocarbons) and creating byproducts [e.g., methane, iron (II), and carbon dioxide]. Plots of contaminants, electron donors, electron acceptors, and byproducts of biodegradation reactions (Figures 4.7 through 4.22) provide strong evidence of these processes.

- Microbial consumption of both native and anthropogenic organic carbon compounds destroys those compounds and creates conditions favorable for reductive dehalogenation. Site chemical and geochemical data provide evidence of anaerobic dehalogenation of TCB, DCB, TCE, and DCE. Normally, the appearance of CB, DCE, and VC in site groundwater provides the primary line of chemical evidence for reductive dehalogenation of parent compounds such as TCB, DCB, and TCE. However, DCB and CB are primary chlorinated contaminants at Site S-1, and the presence does not definitely prove that reductive dechlorination is occurring. However, geochemical indicators have established that groundwater conditions in the source area are optimal for reductive dechlorination to occur. High concentrations of CB and DCB are present in the source area, but only CB appears at significant concentrations downgradient. These data indicate that rapid rates of reductive dechlorination, specifically of DCB, likely is occurring in the source area. In addition, the presence of very low concentrations of ethane and ethene confirm that the dehalogenation of low-level chlorinated ethenes has occurred.

- Elevated chloride concentrations within the CB plume (particularly in the source area) also may indicate dehalogenation reactions, although chloride also can be produced from oxidation of less-chlorinated solvents (i.e., utilization of CB as a substrate). However, elevated chloride concentrations primarily were observed in the anaerobic source area of the contaminant plume and support the occurrence of anaerobic DCB biodegradation.

- Field-biodegradation rates for DCB were estimated using the methods of Buscheck and Alcantar (1995) and Moutoux *et al.* (1996). These rates ranged from 4.6×10^{-3} day^{-1} to 6.74×10^{-2} day^{-1}, equivalent to half-lives of 151 to 10 days.

- Anaerobic microcosm studies were attempted at Site S-1, but the presence of LNAPL in the microcosm matrix prevented the collection of meaningful rate and mechanism data. The purpose of the anaerobic microcosm study was to determine if reducing groundwater conditions were sufficient to promote TCB, DCB, and potentially CB reductive dechlorination. TCB and DCB are reductively dechlorinating as evidence by site geochemical data and observed contaminant trends. The CB dechlorination could not be verified through the results of this study.

Given the available evidence, the dissolved chlorinated benzene plume at Site S-1 exhibits characteristics of a groundwater plume with mixed aerobic and anaerobic behavior. Natural carbon sources, dissolved petroleum hydrocarbons, and possibly some less-chlorinated solvents appear to act as carbon sources. However, CB may also degrade aerobically along the upgradient edge of the contaminant plume and leading edge of the plume. It is possible that TCB and DCB and relatively lower concentrations of TCE and DCE also are oxidized at the upgradient edge of the contaminant plume. Throughout most of the groundwater plume, anaerobic biodegradation processes are predominant. As a result, CB is persistent in downgradient groundwater. The degradation of CB in downgradient areas appears to be limited by the rate of oxygen replenishment from infiltrating rainwater and mixing with oxygenated groundwater at the leading edge of the plume.

SECTION 5

GROUNDWATER FLOW AND CONTAMINANT TRANSPORT MODEL

5.1 GENERAL OVERVIEW AND MODEL DESCRIPTION

In order to help predict the future migration and fate of CB dissolved in groundwater at Site S-1, Parsons ES modeled shallow groundwater flow and the fate and transport of the dissolved CB plume. The modeling effort had three primary objectives: 1) predict the future extent and concentrations of the dissolved contaminant plume by modeling the combined effects of advection, dispersion, sorption, and biodegradation; 2) assess the potential for downgradient receptors to be exposed to contaminants at concentrations above regulatory levels of concern; and 3) if applicable, provide technical support for the natural attenuation remedial option at post-modeling regulatory negotiations. The model was developed using site-specific data and conservative assumptions about governing physical and chemical processes. The model input data are believed to be reasonably conservative so that the actual reduction in contaminant mass caused by natural attenuation should meet or exceed model predictions.

The model code Bioplume III (USEPA, 1998) was used to estimate the potential for dissolved CB migration and degradation by naturally occurring mechanisms operating at the site. The Bioplume III model incorporates advection, dispersion, sorption, and biodegradation to simulate contaminant plume migration and degradation. The model is based upon the US Geological Survey (USGS) Method of Characteristics (MOC) two-dimensional (2-D) solute transport model of Konikow and Bredehoeft (1979). The MOC method has been updated several times, and the most recent modifications (Konikow and Bredehoeft, 1989) were incorporated into the Bioplume III code. The model was developed through a collaboration between USEPA personal at the National Risk Management Research Laboratory (NRMRL) in Ada, Oklahoma and the Air Force Center for Environmental Excellence (AFCEE) at Brooks AFB, Texas.

Bioplume III is an improvement of Bioplume II through the addition of a sophisticated groundwater modeling interface developed by AEi/MicroEngineering, Inc. (EIS). The pre- and post- processor capability of this interface were used to facilitate model development and analysis and presentation of the model results. Bioplume III also has the capability of simulating contaminant biodegradation using multiple electron acceptors (i.e., DO, nitrate, iron (III), sulfate, and carbon dioxide). The transport equation in Bioplume III is solved 6 times to determine model contaminant and electron acceptor concentrations through the application of instantaneous reaction kinetics. Bioplume III can model contaminant biodegradation with first-order, instantaneous, Monod, and zero-order kinetics.

5.2 CONCEPTUAL MODEL DESIGN AND ASSUMPTIONS

On the basis of the data presented in Section 3, the shallow saturated zone was conceptualized and modeled as a heterogeneous, unconfined aquifer. Site geologic and hydrogeologic data were previously summarized to produce hydrogeologic cross-sections of the site (CH2M Hill, 1998). Cross-sections A-A' and B-B' (Figures 3.2 and 3.3) and Figure 3.4 show that the shallow site hydrogeology is influenced by the topography of the top of the lower confining Navarro Clay. The water table is present at approximately 30 feet bgs in the gravelly alluvial sediments on top of the Navarro Formation. A clayey fill material is present above the saturated zone between 5 and 25 feet bgs. Historical data indicate that groundwater elevations have not been high enough for the water table to contact the overlying clayey fill material. The deeper Edwards aquifers appear to be isolated from the shallow aquifer by several hundred feet of Cretaceous Navarro Clay.

The saturated thickness of the alluvial aquifer within the source area in March/April 1998 ranged from approximately 1 to 5 feet. The steep slope of the Navarro surface in the former sump area is reflected in relatively steep hydraulic gradients and relatively high groundwater flow velocities. Groundwater elevations measured in April 1998 suggest that groundwater velocities in the former sump area were approximately 4.6 ft/day. As the saturated thickness of the aquifer increases in the direction of groundwater migration (northeast), the topography of the Navarro Formation surface flattens and groundwater velocities decrease to approximately 0.5 ft/day. The Navarro surface rises above the groundwater table at several locations in the former sump area. However, significant channeling of groundwater and dissolved contaminants is not evidenced by the inferred CB plume (Figures 4.9 and 4.10) or water table surface (Figures 3.5 and 3.6).

Groundwater elevations generally have fluctuated within a two-foot interval since 1990. The uniformity of groundwater fluctuations across the site has resulted in consistent groundwater gradients from year to year. In particular, a hydraulic gradient of 0.0008 ft/ft was observed beneath the residential area before and after pump-and-treat operations. More recently, a significant change in groundwater flow conditions has resulted from the operation of the groundwater pump and treat system, which has created a cone of depression near recovery wells SS003RW114, -RW115, and -RW116. However, the small saturated thickness in the source area likely limits the radius of influence of the pump and treat system, and some dissolved contaminants appear to migrate past the extraction wells toward the northeast.

The primary continuing sources of contamination at Site S-1 are a combination of sorbed and mobile LNAPL. Sorbed, or residual, LNAPL has been smeared above (and presumably below) the water table across the sump area and in a corridor extending approximately 250 feet downgradient from the source (sump) area. The sorbed LNAPL resulted from the former downgradient migration of mobile LNAPL atop the water table; as the water table moved up and down. The mobile LNAPL became sorbed to adjacent soils. CB contamination primarily enters groundwater by direct dissolution from sorbed and mobile LNAPL to groundwater.

CB contamination was the primary focus of this RNA demonstration because of its high concentration and extensive off-base migration. DCBs and TCBs were not evaluated as part of this modeling exercise because they were present at lower concentrations and biodegrade more rapidly than CB. The susceptibility of DCB to both

aerobic and anaerobic biodegradation mechanisms contribute to its rapid decline and minimal concentrations off-base. Groundwater geochemical data indicate that the alluvial aquifer is anaerobic over the extent of the entire CB plume. The combination of dissolved organic contaminants, including CB, and natural organic carbon is causing the microbial depletion of DO concentrations and increasing the reducing potential of the groundwater. Methane was detected in Site S-1 groundwater, indicating the presence of groundwater redox conditions necessary for the reductive dechlorination of DCB, TCB, TCE, and DCE contamination. The reductive dechlorination of DCB enhances CB concentrations in site groundwater.

The loading rates at which CB mass is introduced to the groundwater model were selected to reproduce maximum dissolved CB concentrations detected in recent years. The plume is at least 25 years old because the last reported use of the former sump area was in 1973 (HNUS, 1991). The earliest CB measurements at monitoring wells directly in, or immediately downgradient from the former sump area, were collected in 1995. Between 1995 and 1998, CB concentrations at these same wells were variable, and increasing or decreasing trends are not apparent. This lack of trends suggests that the rate of LNAPL weathering during this time period was insufficient to produce noticeable declines in groundwater contaminant at concentrations in the former sump area. In contrast, CB concentrations at downgradient monitoring wells SS003MW001, SS003MW010, and SS003MW016 have declined since 1989. This trend was apparent even before the pump and treat system was installed in 1995. Therefore, these reductions may have resulted from weathering of LNAPL in the source area, possibly supplemented by above-normal oxygen recharge to the aquifer during wet seasons. On the basis of calculated velocities, changes in CB leaching rates in the source area should not be reflected at monitoring well SS003MW016 for approximately seven to eight years. Therefore, recent declines in downgradient CB concentrations in 1995 and 1996 were probably not caused by the pump-and-treat system, but likely are caused by reduced leaching rates in the source area. To simplify the model, appropriate mass loading rates that reproduced maximum source area CB concentrations (ranging from 11,000 µg/L to 45,000 µg/L in the source area) and the maximum downgradient CB concentration of 49 µg/L in March/April 1998 were used to define calibration targets. Most of the maximum CB concentrations detected at the site were measured during this study.

The most important assumption made when using the Bioplume III code to simulate the CB plume is that dispersion, sorption, and biodegradation all play major roles controlling contaminant fate and transport at the site. Soil TOC data are unavailable, but concentrations of organic carbon are probably low considering the gravelly nature of the alluvial aquifer; therefore, the sorption potential of the aquifer is probably limited. Dispersivity, which is a characteristic of the porous medium, is a measure of the longitudinal and lateral spreading of the contaminant plume caused by local heterogeneities that cause deviations from the average linear migration velocity. The magnitude of dispersion is generally believed to be scale-dependent: the longer the plume flowpath, the greater the dispersion. Given the length of the groundwater plume, it is reasonable to assume that dispersion is an important parameter influencing solute transport in the study area. Dispersion is estimated using mathematical methods and accepted rules-of-thumb. Sorption (assumed to be a linear process) is simulated using a coefficient of retardation, and biodegradation is simulated using groundwater geochemical data or a first-order decay constant (Section 5.1). Selection of values for these model input parameters is discussed in Section 5.3.3.

5.3 INITIAL MODEL SETUP

Where possible, the initial setup for this model was based on site-specific data. Where site-specific data were not available (e.g., effective porosity), reasonable assumptions were made on the basis of widely-accepted literature values for materials similar to those found in the shallow aquifer at Site S-1. The following sections describe the basic model setup. Those model parameters that were varied during model calibration are discussed in Section 5.4.

5.3.1 Grid Design

The model domain for Site S-1 is represented using one layer, with a 30- by 35-cell horizontal grid (Figure 5.1). The maximum grid size that Bioplume III can accommodate is 35 rows by 35 columns. Rectangular grid cells (50 feet by 100 feet) were used to discretize the model domain. The grid was oriented so that the longest dimension (3,500 feet) was parallel to the direction of contaminant migration to the northeast.

The grid thickness ranged from 4.0 to 15.3 feet on the basis of elevation differences between the groundwater table and the surface of the Navarro Formation (Figure 5.2). The thickness data were assigned to the model grid cells through the use of "Log Points" Bioplume III. "Log Points" allow for the graphical assignment of aquifer top and bottom data to the model and subsequent estimation of aquifer thickness with automatic kriging techniques. Figure 5.1 shows the location of the 38 log points used to estimate the aquifer thickness throughout the model domain.

5.3.2 Groundwater Flow Model

5.3.2.1 Boundary Conditions

In defining the model domain, the area of interest must be separated from the surrounding system. Boundary conditions describe the interaction between the system being modeled and its surroundings or, for transport models, the loading of contaminant mass into the system. Boundary conditions are used to include the effects of the system outside the area being modeled with the system being modeled, while at the same time allowing the isolation of the desired model domain from the larger system. In effect, the boundaries of the model tell the area immediately inside the boundaries what to expect from the outside world. The solution of any differential equation requires specification of the conditions at the periphery of the system. Model boundaries are thus mathematical statements that specify the dependent variable (head or contaminant concentration) or the flux (derivative of the head or contaminant concentration with respect to time) at the model grid boundaries.

X-Axis (feet)

Y-Axis (feet)
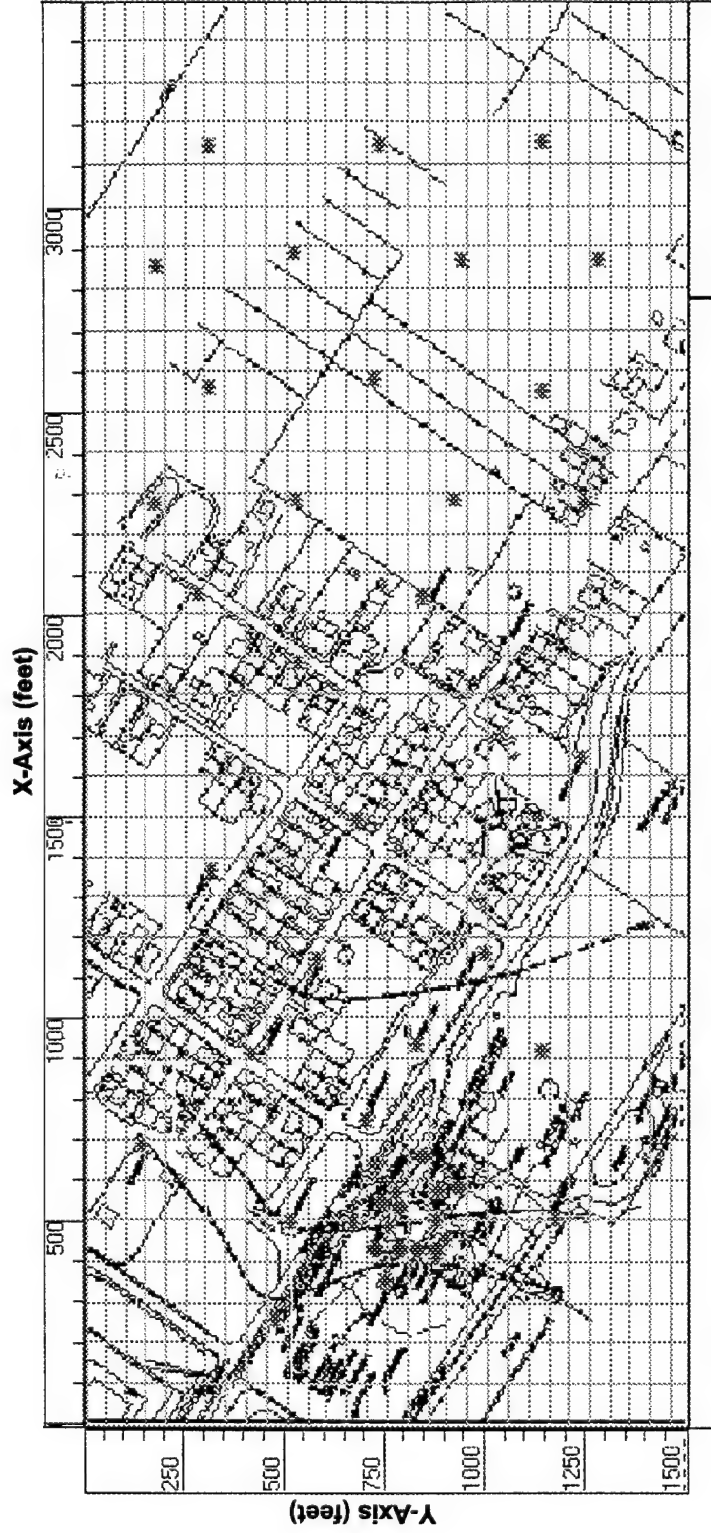
Legend

☐ Model Grid Cell (100 x 50 feet)

✳ Model Extraction or Injection Well Location

※ Model Log-Point Location

Source Cells (Wells):
500x, 750y
500x, 800y
500x, 850y
500x, 900y
600x, 800y

Recovery Wells:
SS003RW014 (600X, 750Y)
SS003RW015 (700X, 850Y)
SS003RW016 (600X, 900Y)

FIGURE 5.1

MODEL GRID

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.

Denver, Colorado

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X-Axis (feet)

Y-Axis (feet)

Legend

	15.297
	14.037
	12.777
	11.518
	10.258
	8.999
	7.739
	6.479
	5.220
	3.960
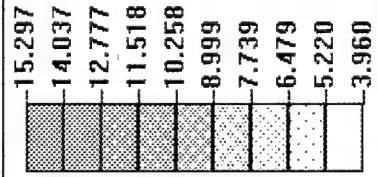
Aquifer Thickness in Feet

FIGURE 5.2

**MODELED
AQUIFER THICKNESS**

Site S-1 MNA TS
Kelly Air Force Base, Texas

**PARSONS
ENGINEERING SCIENCE, INC.**

Denver, Colorado

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Three types of boundary conditions generally are used to describe groundwater flow and solute transport. Boundary conditions are referred to as type one (Dirichlet), type two (Neumann), and type three (Cauchy). Table 5.1 summarizes boundary conditions for groundwater flow and solute transport.

TABLE 5.1
COMMON DESIGNATIONS FOR SEVERAL
IMPORTANT BOUNDARY CONDITIONS[a/]
SITE S-1 MNA TS
KELLY AIR FORCE BASE, TEXAS

Boundary Condition	Boundary Type	Formal Name	General Mathematical Description	
			Groundwater Flow	Contaminant Transport
Specified-Head or Specified-Concentration	Type One	Dirichlet	$H = f(x,y,z,t)$	$C = f(x,y,z,t)$
Specified Flux	Type Two	Neumann	$\frac{\partial H}{\partial n} = f(x,y,z,t)$	$\frac{\partial C}{\partial n} = f(x,y,z,t)$
Head-Dependent or Concentration-Dependent Flux	Type Three (mixed-boundary condition)	Cauchy	$\frac{\partial H}{\partial n} + cH = f(x,y,z,t)$	$\frac{\partial C}{\partial n} + cC = f(x,y,z,t)$

[a/] Modified from Franke *et al.* (1987).

In flow models, boundary conditions are ideally used to specify actual hydrogeologic boundaries to the system, such as streams, lakes, confining units, groundwater divides, or any geologic or anthropogenic feature that may bound a system. Also, the boundaries may be defined as areas where properties (e.g., flux) are known and can be defined. When using a numerical flow model, hydrologic boundaries such as constant-head features (e.g., lakes, etc.) or constant-flux features should, when possible, coincide with the perimeter of the model. In areas that lack obvious hydrologic boundaries, constant-head or constant-flux boundaries can be specified at the numerical model perimeter as long as the perimeter is far enough removed from the contaminant plume that transport calculations will not be affected by inaccuracies in the boundary conditions.

Two different model boundary conditions were used for Site S-1. Specified-head cells were defined at the model boundaries. The specified heads were estimated by projecting heads from the groundwater flow maps. These specified-head cells were placed far enough from the simulated CB plume to avoid potential boundary interference (Figure 5.3). No-flow conditions were specified at the lower boundary of the model where the alluvial aquifer is bounded by the Navarro Formation. No-flow cells also were established at upgradient locations between the specified-head cells and

X-Axis (feet)

Y-Axis (feet)
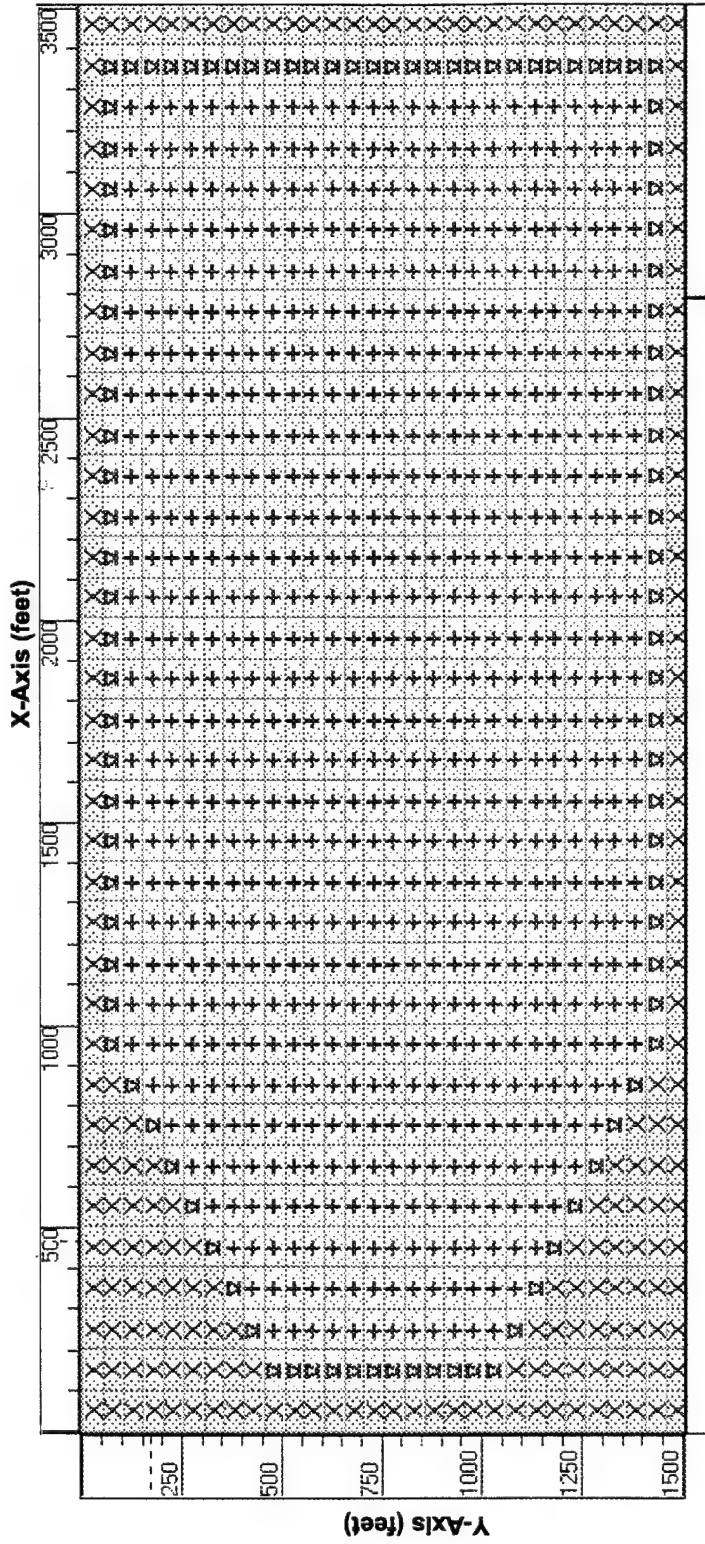
Legend

×   No Flow Cell

☒   Specified - Head Cell

FIGURE 5.3

**MODEL
BOUNDARY CONDITIONS**

Site S-1 MNA TS
Kelly Air Force Base, Texas

**PARSONS
ENGINEERING SCIENCE, INC.**

Denver, Colorado

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the model boundary. These cells were marked as no-flow cells because they were beyond the limits of CB contamination and were essentially "turned-off" to decrease the run-time of the model. The upper model boundary is defined by the simulated water table surface.

5.3.2.2 Aquifer Properties

The effective porosity of the aquifer is the percentage of a rock or sediment through which fluids can travel. A general value of 30 percent for porosity was defined for the model domain on the basis of pumping tests completed at the site (HNUS, 1994). This porosity is typical for the sandy gravelly soils observed at Site S-1 (Anderson and Woesnner, 1992).
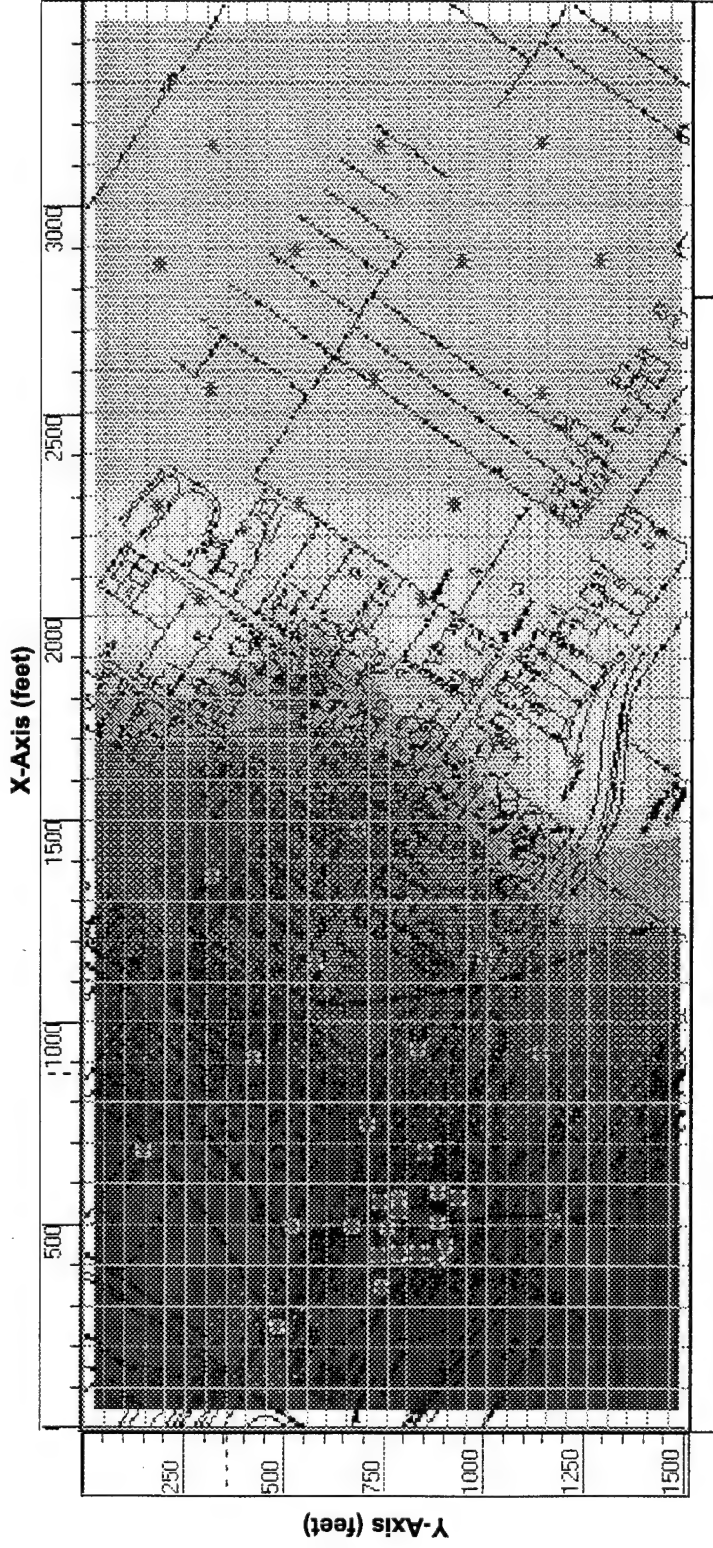
Hydraulic conductivity values were calculated from field data obtained from 13 slug tests and 1 pump test (Section 3.3.1.3). These data indicate variability in hydraulic conductivity of two orders-of-magnitude at the site (0.0071 to 0.673 cm/sec, or 0.00023 to 0.022 feet per second [ft/sec], respectively). Hydraulic conductivity estimates used for the model were obtained from average conductivities along the centerline of the plume. For instance, the average hydraulic conductivity in the former sump area based on slug tests performed at monitoring wells SS003RW004, SS003MW019, and SS003MW020 was 0.00053 ft/sec. In contrast, the average hydraulic conductivity at downgradient wells SS003MW010, SS003MW011 and SS003MW015 was 0.003 ft/sec. Therefore, hydraulic conductivities in the model domain were varied accordingly to obtain a calibrated flow model. The final values of hydraulic conductivity used in the model ranged from 0.00016 to 0.003 ft/sec. Hydraulic conductivity values were attached to each of the 38 log points (Figure 5.1) at the site and interpreted across the model domain by numerical kriging techniques to create a hydraulic conductivity map (Figure 5.4).

5.3.3 Contaminant Transport Model
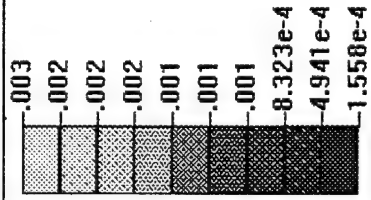
5.3.3.1 Source

Transport models use boundary conditions to express the influence of contaminant sources such as LNAPL bodies and dissolved mass entering through recharge, injection wells, surface water bodies, and leaking structures. Sources such as LNAPL bodies may be represented as specified-concentration boundaries (limited by solubility constraints or observed maximum concentrations) or as specified-flux boundaries (for which the chemical loading rate must be known or estimated). However, in most cases, only the effects of the source are measured, not the source characteristics (Spitz and Moreno, 1996). The source must therefore be represented as a "black box" that produces appropriate contaminant concentrations or fluxes at selected points in the model. The source may be misrepresented under such a scenario, but there is often little choice in the matter. Estimating contaminant flux into groundwater from LNAPL is difficult and is dependent upon several parameters, most of which cannot be measured (Feenstra and Guiguer, 1996; Abriola, 1996).

At Site S-1, the lack of historical data regarding the contaminant source combined with the lack of groundwater quality data in the source area prior to 1995, make it difficult to accurately simulate the source in the model. Therefore, rather than using

X-Axis (feet)

Y-Axis (feet)

Legend

Hydraulic Conductivity (ft/sec)

.003
.002
.002
.002
.001
.001
.001
8.323e-4
4.941e-4
1.558e-4

FIGURE 5.4

MODEL
HYDRAULIC CONDUCTIVITIES

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado

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various calculations to attempt to estimate CB partitioning from NAPL into groundwater, the "black box" source approach was used. Experience modeling contaminated sites as part of the AFCEE Natural Attenuation Initiative for chlorinated solvents has suggested that this is the best method for reproducing observed plumes (Wiedemeier et al., 1998). At Site S-1, the contaminant is assumed to enter groundwater in the study area through contact between groundwater and mobile or residual LNAPL at or below the water table. Partitioning of CB from this source into groundwater was simulated by defining source area recharge concentrations in five model cells located within the former sump area and along the corridor of residual LNAPL that extends from the sump area to the northeast near monitoring well SS003RW114. The concentrations at all source locations were adequate to reduce the maximum observed CB concentrations in the former sump area during the period from 1995 to 1998. Table 5.2 shows historic CB data used as reference concentrations for the model calibration.

5.3.3.2 Dispersivity

Published data summarized by Spitz and Moreno (1996) suggest that, as a rule of thumb, longitudinal dispersivity is approximately one-tenth the travel distance of the plume (from the source to the toe of the plume). However, it has recently been suggested that dispersivity does not vary linearly with plume length, but through a logarithmic relationship to plume length. For purposes of this model, dispersivity values were initially set at 31.7 feet, estimated using an empirical logarithmic technique proposed by Xu and Ecstein (1995) (calculation shown in Appendix C). Transverse dispersivity values were estimated as one-twentieth of the longitudinal dispersivity values, which is below the commonly accepted value of one-tenth of the longitudinal dispersivity (Domenico and Schwartz, 1990). The value was adjusted to reduce abnormally high simulated CB concentrations in cross-gradient wells which have not been measured in the field.

5.3.3.3 Retardation

Retardation of CB relative to the advective velocity of the groundwater occurs when contaminant molecules are sorbed to organic carbon, silt, or clay in the aquifer matrix. Actual TOC values from the site are unavailable. However, a literature-based TOC value of 0.05 percent was assumed (Spitz and Moreno, 1996). Using this TOC value, an assumed bulk density of 1.8 kilograms per liter (kg/L), and a soil sorption coefficient (K_{oc}) for CB of 126 L/kg (Knox et al., 1993; Montgomery et al., 1996), the coefficient of retardation for CB was estimated to be 1.36. The results of the calculations are summarized in Table 5.3 along with calculations for other site contaminants for comparison purposes. The lower the coefficient of retardation, the faster the CB plume will migrate downgradient. The retardation coefficient of 1.36 for CB was assigned to the model and was not adjusted during the calibration process.

5.3.3.4 Biodegradation

As discussed in Section 4.5, first-order decay rates of 1.9×10^{-2} day^{-1} to 7.9×10^{-4} day^{-1} were calculated for CB using site-specific data. These rates were used to define a range of possible values for model input. An initial estimate of 2.7×10^{-3} days^{-1} was defined for the model domain. The model could not be adequately calibrated using

TABLE 5.2
CALIBRATED VERSUS OBSERVED
CHLOROBENZENE CONCENTRATIONS
SITE S-1 MNA TS
KELLY AIR FORCE BASE, TEXAS

Calibrated Well Location	Sampling Dates	CB Concentration ($\mu g/L^{a/}$)*	Calibrated CB Concentrations ($\mu g/L$)
Source Area			
SS003MW050	3/7/97	**20,000**	20,290
	6/26/97	1,450	
	8/19/97	14,400	
	3/24/98	11,000	
	6/18/98	14,000	
SS003MW272	4/1/98	**45,000**	47,190
SS003MW121	6/26/97	3,480	
	3/19/98	**14,000**	12,890
SS003MW273	4/1/98	**21,000**	20,900
SS003MW110	9/28/94	5	
	8/15/95	1,300	
	12/14/95	1,740	
	6/27/96	9,535	
	8/14/96	**11,000**	10,660
	12/31/96	8,400	
	3/7/97	7,500	
	6/26/97	10,300	
	8/19/97	10,100	
	3/27/98	5,400	
DOWNGRADIENT			
SS003MW001	7/18/89	13,000	
	1/8/90	11,000	
	10/5/90	9,000	
	12/14/95	1,300	
	12/13/96	2,400	
	3/11/97	1,400	
	6/26/97	3,460	
	11/1/97	**3,500**	5,800
	3/25/98	790	
	6/18/98	830	
SS003MW010	8/3/89	610	
	11/30/89	420	
	10/4/90	280	
	12/14/95	8	
	12/18/96	26	
	3/11/97	28	
	11/1/97	10	
	3/30/98	**45**	530
	6/18/98	5	
SS003MW016	11/29/89	610	
	1/8/90	450	
	10/5/90	600	
	12/14/95	14	
	11/1/97	1	
	3/26/98	**49**	46
	6/18/98	1	

a/ $\mu g/L$ =migrograms per liter.

*Note: Bold value indicates the CB concentration used for model calibration.

TABLE 5.3
CALCULATION OF RETARDATION COEFFICIENTS[a]
SITE S-1 MNA 'TS
KELLY AIR FORCE BASE, TEXAS

Compound	Molecular Weight	K_{oc} (L/kg [a])	Fraction Organic Carbon [b]	Distribution Coefficient K_d (L/kg)	Distribution Coefficient K_d (ft^3/kg)	Bulk Density (kg/L) [c]	Bulk Density (kg/ft^3)	Porosity [d]	Coefficient of Retardation
Chlorobenzene	112.56	126	0.0005	0.063	0.00222	1.72	48.70	0.30	1.36
1,2-Dichlorobenzene	147	186	0.0005	0.093	0.00329	1.72	48.70	0.30	1.53
1,3-Dichlorobenzene	147	170	0.0005	0.085	0.00300	1.72	48.70	0.30	1.49
1,4-Dichlorobenzene	147	159	0.0005	0.079	0.00280	1.72	48.70	0.30	1.45
Benzene	84	79	0.0005	0.040	0.00140	1.72	48.70	0.30	1.23
Toluene	98	190	0.0005	0.095	0.00336	1.72	48.70	0.30	1.54

NOTES:

[a] From technical protocol (Wiedemeier et al., 1996); Knox et al. (1993); and Montgomery et al.. (1990).

[b] Estimated from literature values for sand, and gravel (Spitz and Moreno, 1996).

[c] Assumes an aquifer grain density of 2.65 (quartz sand) and a volumetric porosity of 35%.

[d] A porosity of 0.3 was estimated from previous pumping tests at the site (Section 3).

instantaneous reaction kinetics as described in Section 5.1. Therefore, first-order kinetics were used instead.

5.4 MODEL CALIBRATION

Model calibration is an important component in the development of any numerical groundwater model. Calibration of the flow model demonstrates that the model is capable of matching hydraulic conditions observed at the site; calibration of a contaminant transport model superimposed upon the calibrated flow model helps demonstrate that contaminant loading and transport conditions are being appropriately simulated. Model input and output are included in Appendix D.

5.4.1 Groundwater Flow Model

The average groundwater elevations computed using data from March 1990, March 1995, and April 1998 (Figure 5.5) were used to calibrate the groundwater model for steady-state conditions. The three selected measurement events represent similar seasons for which a relatively large data set was available. Average groundwater elevation data were used to more accurately simulate hydraulic gradients, groundwater flow directions, and the saturated thickness of the aquifer. For example, the use of average elevation data was helpful for simulating the advection and loading characteristics of the aquifer in the thin saturated zones underlying the source area, where accurate estimation of aquifer thickness is most critical. The groundwater model was calibrated under natural flow conditions without hydraulic stresses caused by pump-and-treat system operation.

Water level elevation data from 18 monitoring wells were used to compare measured and simulated heads for calibration. The selected locations were SS003MW001, SS003MW004, SS003MW006, SS003MW007, SS003MW010, SS003MW011, SS003MW013, SS003MW014, SS003MW015, SS003MW016, SS003MW019, SS003MW020, SS003MW021, SS003MW050, SS003MW053, SS003MW120, SS003MW121, and SS003RW202.

The numerical flow model was calibrated by altering hydraulic conductivity, and constant-head elevations at the model boundaries in a trial-and-error fashion until simulated heads approximated observed field values within a prescribed accuracy. Figure 5.6 shows the calibrated water table. Calibrated model hydraulic conductivities ranged 0.00016 to 0.003 ft/sec (Section 5.3.2.2).

The root mean squared (RMS) error is commonly used to express the average difference between simulated and measured heads. RMS error is the average of the squared differences between measured and simulated heads, and can be expressed as:

$$\text{RMS} = \left[\frac{1}{n} \sum_{i=1}^{n} \left(h_m - h_s \right)_i^2 \right]^{0.5}$$

where: n = the number of points where heads are being compared,
h_m = measured head value, and
h_s = simulated head value.

FIGURE 5.5

AVERAGE GROUNDWATER
ELEVATIONS
(MARCH 1990, 1995 AND
APRIL 1998)

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado

LEGEND

MONITORING WELL LOCATION
"RW" IDENTIFIER INDICATES
A RECOVERY WELL

660 — LINE OF EQUAL GROUNDWATER ELEVATION
FEET ABOVE MEAN SEA LEVEL
(DASHED WHERE INFERRED)

INFERRED GROUNDWATER FLOW DIRECTION

LEGEND

◆ MONITORING WELL LOCATION
"RW" IDENTIFIER INDICATES
RECOVERY WELL

659' LINE OF EQUAL SIMULATED GROUNDWATER
ELEVATION FEET ABOVE MEAN SEA LEVEL

INFERRED GROUNDWATER
FLOW DIRECTION

FIGURE 5.6

CALIBRATED GROUNDWATER
ELEVATIONS

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.

Denver, Colorado

0   125   250   500
FEET

The RMS error between observed and calibrated values at the 18 comparison points was 0.66 feet, which corresponds to a calibration error of 9.9 percent (water levels dropped approximately 6.1 feet over the portion of the model domain containing the monitoring wells listed above). March/April 1998 groundwater elevations noticeably affected by drawdown associated to pump-and-treat operations were not used in the above RMS error calculation (e.g., SS003RW202, SS003TW114, SS003MW001, SS003RW115, and SS003MW004). Interestingly, the calibrated model was relatively accurate in simulating the groundwater elevations averaged from a larger set of groundwater level measurements which included the effects of the groundwater pump-and-treat since 1995 (July 1989, March 1990, October 1990, November 1990, March 1995, December 1995, May 1997, October 1997, April 1998, and June 1998). The RMS error for this data set was 0.83 feet, corresponding to a calibration error of 12.2 percent (average historic difference in groundwater elevations measured from the above-listed monitoring wells).

In solving the groundwater flow equation, Bioplume III establishes the water table surface and calculates an overall hydraulic balance that accounts for the numerical difference between flux into and out of the system. The hydraulic mass balance for the calibrated model was adequate to accomplish the objectives of this modeling effort, with 99.61 percent of the water flux into and out of the system being numerically accounted for (e.g., 0.39-percent error).

5.4.2 Plume Calibration For Model Kelly-A

After calibration of the flow model, the numerical solute transport model was calibrated by altering the specified CB-flux rates at 5 model injection wells (placed in the source area) in a trial-and-error fashion until the simulated plume approximated observed field values. While the term "injection well" suggest that contaminants are being introduced at a point, Bioplume III assumes that contamination introduced at a well instantly equilibrates throughout the entire cell in which the well is located. The locations of the simulated injection wells are shown on Figure 5.1. Locations of simulated injection wells were based on the known location of the former sump area and the corridor of residual LNAPL extending northeast from the sump. The injected CB concentrations were proportional to the maximum groundwater CB concentrations measured at the site. The injection rate for each well was set at 0.01 gallons per minute (gpm), a value low enough that the flow calibration and water balance were not affected. The transport parameters varied during plume calibration were injection well concentrations, plume transverse dispersivity, and biodegradation rate. Because the original estimates for these parameters resulted in a calculated plume that reasonably resembles the existing groundwater plume, these parameters were not varied greatly.

CB concentrations measured at the eight monitoring wells listed in Table 5.2 were used to calibrate the contaminant transport model. Table 5.2 also shows historic CB concentrations, measured CB concentrations used as calibration targets, and calibrated CB concentrations. Not all monitoring wells containing CB contamination were used in the calibration process because the Bioplume III model is limited to a maximum model grid size of 35 by 35 cells of identical dimension. This limitation required the use of large model cells to extend the grid throughout the CB plume area. Some source area cells contain up to three monitoring wells. For this reason, not every measured CB concentration will "match" the calibrated CB plume. The calibration effort focused on

obtaining a good correlation between observed and calibrated CB concentrations in the source area and at the leading edge of the plume.

The maximum CB concentrations in the source area selected as calibration targets were measured between September 1994 and June 1998 (Table 5.2). Selection of these maximum values lends a conservative bias to the model is justified because historical data do not indicate clear decreases in groundwater CB concentrations in the source area. Relatively recent CB concentrations (collected between November 1997 and June 1998) that reflect plume trends over the past 2.5 years were evaluated to select calibration targets in downgradient wells. This model was run for a 15-year simulation to achieve stabilized conditions.

The calibrated plume (Model Kelly-A; Figure 5.7) has similar, but not identical, concentrations to selected maximum CB concentrations measured in the field samples. In terms of size as measured by the 10 µg/L contour, the calibrated CB plume is slightly longer and wider than observed in March/April 1998 (Figure 4.9), but is similar to the shape of the measured plume. The highest simulated CB concentration occurred at monitoring well SS003MW272, with a calibrated CB concentration of 47,190 µg/L versus a measured value of 45,000 µg/L. Simulated source area CB concentrations were within several hundred µg/L maximum measured concentrations, with the exception of monitoring well SS003MW121 (calibrated concentration approximately 1,110 µg/L lower than measured concentration). Simulated source area concentrations generally differed from measured maximum CB concentrations by no more than 0.05 to 4.8 percent.

At downgradient locations, the simulated CB plume was conservative with respect to observed CB concentrations. For example, modeled CB concentrations at monitoring well SS003MW001 and SS003MW010 exceeded observed concentrations by approximately 2 to 10 times. The size of the model grids cells (50 by 100 feet) limits the resolution of the groundwater model and promotes some widening of the groundwater plume. As a result, simulated CB concentrations at monitoring wells SS003MW001 and SS003MW010 are higher than measured concentrations. The calibrated groundwater plume was closely matched the measured plume near monitoring well SS003MW016, where calibrated and observed CB concentrations were 46 and 49 µg/L, respectively. In general, simulated CB concentrations at the plume toe exceeded most observed CB concentrations measured since December 1995.

5.4.3 Plume Calibration For Models Kelly-B and Kelly-C

Two additional groundwater models were created with different calibration goals than used in model Kelly-A. Model Kelly-B was calibrated using similar source area CB concentrations to Model Kelly-A, but maximum downgradient CB concentrations were increased to approximately 610 µg/L (CB concentration measured at monitoring well SS003MW016 in November 1989). This model scenario was developed as a worst-case simulation using the highest CB concentrations ever observed at Site S-1. Model Kelly-C also used similar source area CB concentrations to Model Kelly-A, but used averaged CB concentrations from December 1995 to June 1998 at monitoring well SS03MW016. The use of average concentrations at monitoring well SS003MW016 for Model Kelly-C allowed for greater model realism (e.g., plume length more closely matched recent observations) based on recent plume trends.

LEGEND

✛ MONITORING WELL LOCATION

⬆ INFERRED GROUNDWATER
FLOW DIRECTION

LINE OF EQUAL SIMULATED
CHLOROBENZENE CONCENTRATION
$(\mu g/L)$

>20,000 $\mu g/L$
>10,000 $\mu g/L$
>1,000 $\mu g/L$
>100 $\mu g/L$
>10 $\mu g/L$

FIGURE 5.7

CALIBRATED
CHLOROBENZENE PLUME
MODEL KELLY-A

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.

Denver, Colorado

0   125   250   500
FEET

The biodegradation rate for model Kelly-B was decreased from 2.7×10^{-3} day^{-1} to 1.3×10^{-3} day^{-1} to achieve model calibration. The results of the model calibration are shown in Figure 5.8. The final calibration of model Kelly-B achieved a CB concentration of 599 µg/L at monitoring well SS003MW016. Groundwater CB concentrations stabilized at concentrations below 100 µg/L approximately 700 feet northeast of monitoring well SS003MW016. This model indicated that previously-measured downgradient CB concentrations that were much higher than those measured more recently were stabilized by natural attenuation processes before migrating to downgradient receptors. Groundwater CB concentrations at Site S-1 were at a maximum in 1989, but since haven't exceeded these levels. Therefore, calibration of model Kelly-B is overly conservative with respect to recent CB concentrations, and was not used for future fate and transport estimates.

The biodegradation rate for model Kelly-C was increased from 2.7×10^{-3} day^{-1} to 3.1×10^{-3} day^{-1} during model calibration. The model calibration achieved a CB concentration of 14 µg/L at monitoring well SS003MW016 and closely matched recent average plume trends. The calibrated CB plume for model Kelly-C was 300 feet shorter than for model Kelly-A. Both models Kelly-A and Kelly-C were used for fate and transport predictions of groundwater CB contamination. However, model Kelly-A provides the best simulation of plume trends by using maximum CB concentrations that were measured either in the source area or at the toe of the plume since December 1995 and that may occur again in the near future. Model Kelly-A was used as the primary model for this TS to simulate the effects of source removal (see Section 6). As a comparison, similar model simulations were performed with model Kelly-C and are documented in Appendix F.
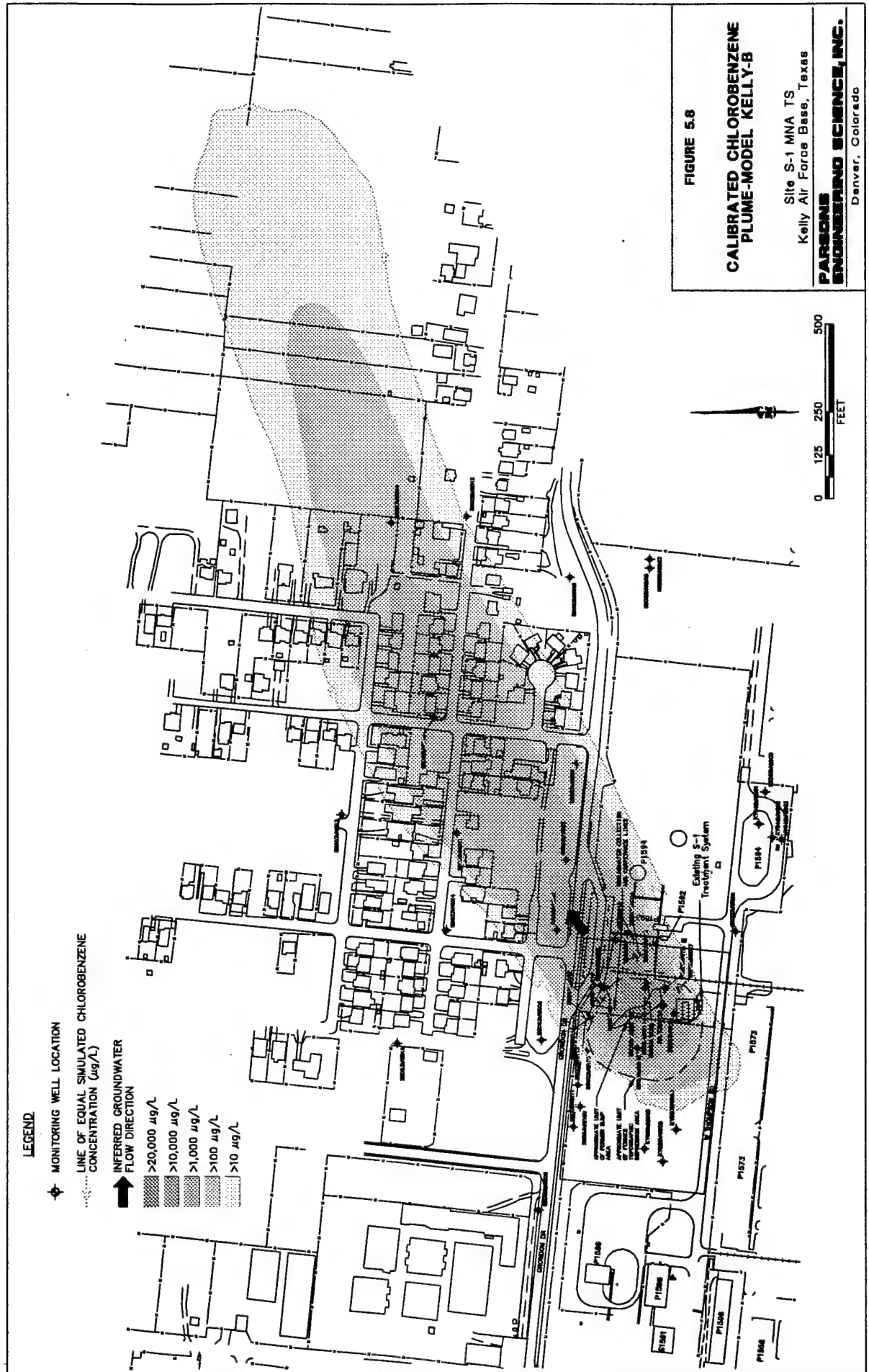
5.5 SENSITIVITY ANALYSIS

The purpose of the sensitivity analysis is to determine the effect of varying model input parameters on model output. The sensitivity analysis was conducted by varying hydraulic conductivity, the coefficient of retardation, the first-order decay rate, dispersivity, and the CB injection rate.

To perform the sensitivity analyses, calibrated model Kelly-A was adjusted by systematically changing the aforementioned parameters individually, and then comparing the new simulations to the results of the calibrated model. The models were run for a 15-year period, just as the calibrated model was, so that the independent effect of each variable could be assessed. Eight sensitivity runs of the calibrated model were made, with the following variations:

A. Hydraulic conductivity uniformly increased by a factor of 2;

B. Hydraulic conductivity uniformly decreased by a factor of 2;

C. Dispersivity uniformly increased by a factor of 2;

D. Dispersivity uniformly decreased by a factor of 2;

E. Coefficient of retardation uniformly increased by a factor of 2;

LEGEND

◆ MONITORING WELL LOCATION

.... LINE OF EQUAL SIMULATED CHLOROBENZENE
CONCENTRATION ($\mu g/L$)

↑ INFERRED GROUNDWATER
FLOW DIRECTION

>20,000 $\mu g/L$
>10,000 $\mu g/L$
>1,000 $\mu g/L$
>100 $\mu g/L$
>10 $\mu g/L$

FIGURE 5.8

CALIBRATED CHLOROBENZENE
PLUME-MODEL KELLY-B

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado

0   125   250   500
FEET

F. Coefficient of retardation uniformly decreased by a factor of 2;

G. First-order decay rate increased by an order of magnitude; and

H. First-order decay rate decreased by an order of magnitude.

The results of the sensitivity analyses are discussed in the following subsections. As described in the following paragraphs, the parameter modifications listed above generally resulted in significant changes in the resulting plumes, with the retardation modifications having the smallest effect.

5.5.1 Sensitivity to Variations in Hydraulic Conductivity

Hydraulic conductivity is an important aquifer characteristic that represents the ability of the water-bearing strata to transmit groundwater. An accurate estimate of hydraulic conductivity is important to help quantify advective groundwater flow velocities and to define the flushing potential of the aquifer. As a result, models used to estimate contaminant transport are particularly sensitive to variations in hydraulic conductivity. Lower values of hydraulic conductivity result in a slower-moving plume. Higher values of hydraulic conductivity result in a faster-moving plume. The effects of varying hydraulic conductivity are summarized in Table 5.4. Uniformly increasing the hydraulic conductivity by a factor of two increased both the lateral and longitudinal spread of the plume. The increased groundwater velocities in the source area also decreased source area CB concentrations by decreasing the groundwater residence time. For instance, the simulated concentration at monitoring well SS003MW272 decreased from 47,190 µg/L to 26,260 µg/L with the increased hydraulic conductivity. In contrast, decreasing the hydraulic conductivity by a factor of two slowed overall plume migration, and caused the contaminant mass to be concentrated within a smaller area. As a result, CB levels in the source area increased (monitoring well SS003MW272 increased from 47,190 µg/L to 64,110 µg/L) and the simulated CB concentrations downgradient decreased (monitoring well SS003MW006 decreased from 46 µg/L to <1 µg/L).

5.5.2 Sensitivity to Variations in Dispersivity

The effects of varying dispersivity are summarized in Table 5.4. Both longitudinal and transverse dispersivity were varied for this analysis, as the ratio of the two values was kept constant at 0.05. Increasing the dispersivity by a factor of two resulted in lower concentrations in the source area. The simulated concentration at source area monitoring well SS003MW272 was 38,760 µg/L, compared to a calibrated concentration of 47,190 µg/L. Corresponding increases were observed downgradient from the source area as a result of increased spreading of the plume, causing the simulated concentration at downgradient well SS003MW016 to increase to 56 µg/L. Increasing the dispersivity also caused a corresponding increase in the width of the plume.

Decreasing the dispersivity by a factor of two produced a plume with slightly higher concentrations in the source area as less mass was discharged from the source area via mechanical and molecular diffusion. The simulated concentration at monitoring well

TABLE 5.4
SENSITIVITY ANALYSIS RESULTS
SITE S-1 MNA TS
KELLY AIR FORCE BASE, TEXAS

Well No.	Calibrated CB plume Concentration $(\mu g/L)$[a]	$K \times 2$[b]	$K/2$	$\alpha \times 2$[c]	$\alpha/2$	Retardation Increased by 2	Retardation Decreased by 2	Decay Rate by by 10X	Decay Rate Decreased by 10X
Length of CB plume (Source Area to Edge of Plume in feet)									
SS003MW272	47190	26260	64110	38760	52990	42020	48290	12720	67950
SS003MW273	20900	13760	25220	19820	21530	19090	22860	3060	37380
SS003MW001	5800	4300	3700	5300	6700	3600	7300	35	20500
SS003MW011	346	690	34	442	279	174	535	<1	4900
SS003MW010	530	1640	35	564	477	204	853	<1	19660
SS003MW016	46	163	<1	56	40	9	97	<1	13190
Width of CB Plume in feet									
SS003MW009	43	147	20	127	17	25	85	<1	586
SS003MW011	346	692	34	442	279	174	535	<1	4900

a/ $\mu g/L$ = micrograms per liter.

b/ K = hydraulic conductivity.

c/ α = dispersivity.

SS003MW272 increased to 52,990 µg/L. The simulated CB concentrations in the downgradient portion of the plume, and the width of the plume, decreased.

5.5.3 Sensitivity to Variations in the Coefficient of Retardation

The effects of varying the coefficient of retardation are summarized in Table 5.4. Uniformly increasing the coefficient of retardation by a factor of 2 slightly limited the downgradient migration of the plume. Slowing plume migration is in this way should have an effect similar to that caused by decreasing the hydraulic conductivity or dispersivity. Specifically, CB concentrations in the source area should increase due to increased groundwater residence times, and downgradient CB concentrations should decrease. Downgradient concentrations did decrease (CB at monitoring well SS003MW016 dropped from 46 to 9 µg/L). However, CB concentrations in the source area also decreased. The simulated decrease in source area concentrations may result from the fact that CB concentrations in a given model cell are biodegraded to a greater degree due to the longer residence time. In contrast, decreasing the coefficient of retardation by a factor of 2 slightly increased plume migration, and also caused an increase in source area CB concentrations. Overall, varying the coefficient of retardation within a reasonable range has a limited effect on contaminant transport.

5.5.4 Sensitivity to Variations in the Anaerobic Decay Rate Constant

The effects of varying the first-order CB decay rate are summarized in Table 5.4. Increasing this parameter by an order of magnitude results in greatly increased degradation of dissolved contaminants. The resulting CB concentrations simulated at source area well SS003MW272 and at downgradient well SS003MW016 were lower than in the calibrated model (12,720 and 0 µg/L, respectively). Increasing the degradation rate by an order of magnitude also results in a much smaller plume. In contrast, decreasing this parameter by an order of magnitude causes a large increase in CB concentrations throughout the entire plume. For instance, groundwater CB concentrations at monitoring wells SS003MW272 and SS003MW016 increased to 67,950 and 13,190 µg/L, respectively. The width of the plume also increased.

5.5.6 Summary of Sensitivity Analysis Results

The results of the sensitivity analysis suggest that the calibrated model depicted in Figure 5.7 is reasonable. Varying the model parameters within the prescribed ranges generally caused the extent and magnitude of the dissolved plume to differ substantially from observed site conditions. The plume is most sensitive to changes in hydraulic conductivity and first-order decay rate. These parameters were manipulated in the model within the range of measured and estimated values for the site (Sections 3.3.1.1 and 4.7, respectively). Although dispersion and retardation affect the migration of the CB plume to a lesser degree, the values chosen for these models are reasonable and based on commonly-accepted literature values or calculated values; these values were not manipulated during the calibration process.

SECTION 6

EVALUATION AND APPLICATION OF MONITORED NATURAL ATTENUATION

The intent of this treatability study is to determine if MNA of groundwater is an appropriate remedial technology to consider when developing final remedial strategies for Site S-1 at Kelly AFB. The MNA alternative consists of three components:

- Processes of natural attenuation to remediate the groundwater contamination and attain remedial goals;

- Institutional controls to prevent exposure to contaminated groundwater; and

- LTM to assess site conditions over time, confirm the effectiveness of natural attenuation processes at reducing contaminant mass, monitor compliance with regulatory requirements, and evaluate the need for additional remediation.

The occurrence of natural attenuation processes that remediate groundwater at Site S-1 is demonstrated in Section 4. In Section 5, a numerical groundwater flow and CB fate and transport model was calibrated for Site S-1 which suggests that the groundwater plume has stabilized, and will diminish under the effects of proposed source treatment. The use of this calibrated model to predict the effectiveness of source remediation activities at Site S-1 is evaluated in this section and fulfills report objectives 3 and 4 listed in Table 1.1. In addition, this section is devoted to evaluation of the future effectiveness of the MNA alternative.

6.1 REMEDIAL GOALS FOR GROUNDWATER

The MNA strategy assumes that compliance with promulgated, single-point remediation goals (e.g., promulgated groundwater standards) is not necessary if site-related contamination does not pose a threat to human health or the environment (i.e., the exposure pathway is incomplete). Therefore, a point of compliance (POC) for remedial goals is chosen at a location between the contaminant source and potential receptor exposure points. The primary remedial action objective for shallow groundwater within and downgradient from Site S-1 is limiting plume expansion to prevent exposure of downgradient receptors to concentrations of CB in groundwater at levels that exceed applicable regulatory standards.

Groundwater at Site S-1 has been designated by the State of Texas as a potential drinking water source, and the development of groundwater remediation goals in the FS will likely reflect this mandate. However, no potable groundwater wells have been

identified in the Site S-1 area, and groundwater from the shallow aquifer is not a commonly accepted potable water source (SAIC, 1996). Because the depths to the water table are generally greater than 25 feet bgs, there are no completed pathways to ecological receptors (e.g., plants with root systems extending to the water table). Because potable or industrial wells are not likely to be placed at Site S-1 and ecological receptor pathways are incomplete, this MNA strategy assumes that potential receptor exposure points are those surface water bodies identified downgradient. The nearest natural groundwater receptor exposure point at Site S-1 is Apache Creek, located 11,400 feet northeast of the Base (CH2M Hill, 1997).

Preliminary remediation goals (PRGs) for the site are based on Texas Industrial Waste Management Regulations presented in the Texas Administrative Code, Title 30, Part IX, Chapter 335, Subpart S-Risk Reduction Standards. Texas Risk Reduction Standard 2 values were identified as the appropriate PRGs to be used for the site until proposed FS groundwater cleanup levels (Risk Reduction Standard 3 values) are established (CH2M Hill, 1997). The Texas Risk Reduction Standard 2 values are health-based groundwater standards identical to those used for Federal maximum contaminant levels (MCLs) for groundwater. Table 6.1 identifies Texas Risk Reduction Standard 2 values applicable to compounds detected at Site S-1. CB concentrations above Standard 2 values will be used as the trigger at point-of-compliance locations discussed later in this section as part of the LTM program discussion. Other groundwater regulations that are potentially applicable to Site S-1 for soil and groundwater remediation are summarized in Appendix A. This summary was taken from the final draft of the FFS prepared for Site S-1 (CH2M Hill, 1997).

TABLE 6.1
POINT-OF-COMPLIANCE REMEDIATION GOALS
SITE S-1 MNA TS
KELLY AIR FORCE BASE, TEXAS

Compound	Texas Risk Reduction Standard 2 (µg/L)	Federal MCL (µg/L)
Chlorobenzene	100	100
1,2-Dichlorobenzene	600	600
Benzene	5	5
Toluene	1,000	1,000
TCE	0	5
PCE	0	5

Source: CH2M Hill, 1997.

6.2 NATURAL ATTENUATION AND SOURCE REMEDIATION MODELING

6.2.1 MODEL APPLICATION TO SITE S-1

Personal communications with Kelly AFB personnel have indicated that source excavation and possibly SVE will be implemented at Site S-1. SVE will be implemented after excavation activities should it be deemed necessary. The exact locations to be excavated and the design of the SVE system will be presented in the CMS. For modeling

purposes, it was assumed that source excavation would be limited to the soils adjacent to monitoring well SS003MW272 where a substantial zone of residual LNAPL was detected (Section 4.1). This excavation area coincides with the heart of the former sump area and is represented in Figure 5.1 by model cell 500x by 850y. An immediate 90-percent source reduction was assumed to occur at this model cell location. Conceptually, a source removal of this magnitude will require excavation of the overlying clay fill and the underlying alluvial material to below the groundwater table.

Considering the size of the source area (up to 12,500 square feet), it was assumed that the entire source would not be excavated. The areas not treated by source excavation were assumed to be remediated through SVE. Four model source cells were reduced at rates considered appropriate to the application of SVE. Under the influence of SVE, it was assumed that sorbed CB contamination and isolated patches of LNAPL remaining in the vadose zone would be removed at a geometric rate of 53.5 percent per year. The selection of this geometric rate is equivalent to a 90 percent reduction in source mass after 4 years of SVE operation.

Following source remediation, soils were assumed to weather at a continued natural geometric weathering rate of 3 percent per year. Although it is realistic to assume that the source strength will decrease over time due to the effects of leaching and weathering/degradation, the rate of decrease can only be estimated due to the dynamic site conditions. Cohen and Mercer (1993) state that the factors influencing NAPL dissolution and eventual depletion include the effective aqueous solubility of LNAPL components, groundwater velocity, LNAPL-water contact area, and the molecular diffusivity of the LNAPL chemicals in groundwater. The actual dissolution of LNAPL will generally slow with time due to aging and reduction of the LNAPL-water contact area (Powers *et al.*, 1991). Volatilization is another physical affect contributing to LNAPL weathering. Considering the age of the source (>25 years) and the contribution of source remediation, it was assumed that a moderately low 3 percent per year weathering rate was a reasonable estimate.
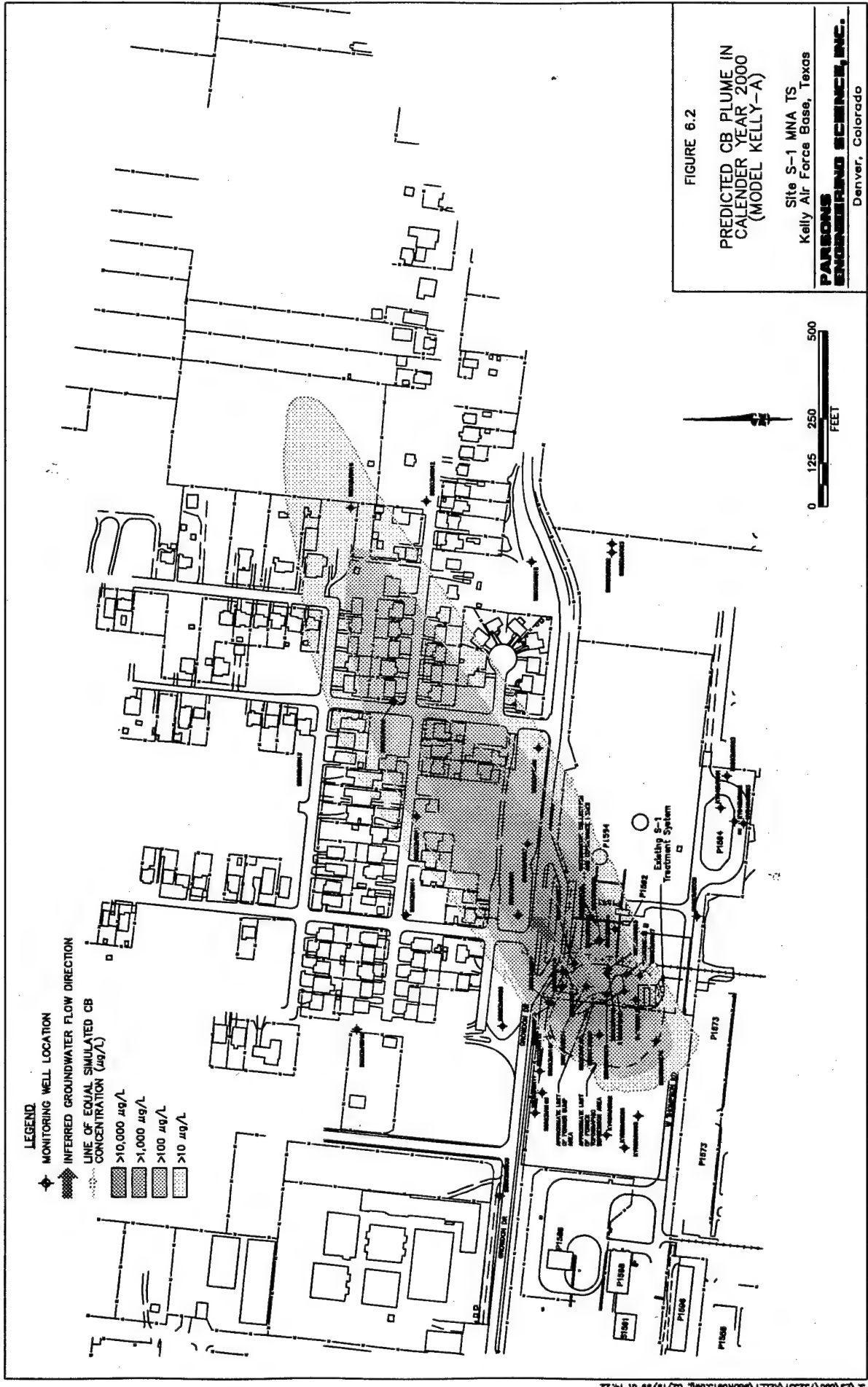
SVE only is applicable at Site S-1 within the alluvial strata. This water bearing layer is comprised of clayey gravel and basal gravel. Soils of this type are highly amenable to the application of negative pressure required for effective SVE as the induced vapor flow volatilizes adsorbed and free-phase contaminants and removes them from the liquid phase. The overlying fill material is composed of clay, silt, and fine sand that is less permeable and resistant to the application of vacuum pressure. It is conceivable that the remediation of the alluvial zone could be compromised by leachate migration from adsorbed or occluded LNAPL in the overlying clayey fill layer.

6.2.2 Effectiveness

Figures 6.1 through 6.5 present the migration of the calibrated CB plume over time predicted by Model Kelly-A. These figures present a time sequence of the size and relative concentrations of dissolved CB as the effects of source remediation are experienced. Groundwater pump and treat operations were assumed to operate from calendar years 1995 to 2000, whereas source remediation activities were assumed to

LEGEND

▲ MONITORING WELL LOCATION

↑ INFERRED GROUNDWATER FLOW DIRECTION

LINE OF EQUAL SIMULATED CB CONCENTRATION (µg/L)

>20,000 µg/L
>10,000 µg/L
>1,000 µg/L
>100 µg/L
>10 µg/L

FIGURE 6.1

PREDICTED CB PLUME IN CALENDAR YEAR 1999 (MODEL KELLY-A)

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado

LEGEND

⬥ MONITORING WELL LOCATION

⬆ INFERRED GROUNDWATER FLOW DIRECTION

⬚ LINE OF EQUAL SIMULATED CB
CONCENTRATION (μg/L)

▓ >10,000 μg/L
▒ >1,000 μg/L
░ >100 μg/L
· >10 μg/L

FIGURE 6.2

PREDICTED CB PLUME IN
CALENDER YEAR 2000
(MODEL KELLY-A)

Site S-1 MNA TS
Kelly Air Force Base, Texas

**PARSONS
ENGINEERING SCIENCE, INC.**

Denver, Colorado

0   125   250   500

FEET

LEGEND

✦ MONITORING WELL LOCATION

➡ INFERRED GROUNDWATER
FLOW DIRECTION

⋯⋯ LINE OF EQUAL SIMULATED CB
CONCENTRATION (μg/L)

▓ >100 μg/L

░ >10 μg/L

FIGURE 6.3

PREDICTED CB PLUME IN
CALENDAR YEAR 2004
(MODEL KELLY-A)

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.

Denver, Colorado

0   125   250   500

FEET

Existing S-1
Treatment System

LEGEND

＋ MONITORING WELL LOCATION

➤ INFERRED GROUNDWATER
   FLOW DIRECTION

∴∴∴ LINE OF EQUAL SIMULATED CR
   CONCENTRATION (μg/L)

▨ >100 μg/L
▨ >10 μg/L

FIGURE 6.4

PREDICTED CB PLUME IN
CALENDAR YEAR 2009
(MODEL KELLY-A)

Site S-1 MNA TS
Kelly Air Force Base, Texas

**PARSONS
ENGINEERING SCIENCE, INC.**
Denver, Colorado

0   125   250   500
FEET

FIGURE 6.5

PREDICTED CB PLUME IN
CALENDER YEAR 2019
(MODEL KELLY-A)

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado

6-R

LEGEND

MONITORING WELL LOCATION

INFERRED GROUNDWATER FLOW DIRECTION

LINE OF EQUAL SIMULATED CB
CONCENTRATION (µg/L)

>100 µg/L

>10 µg/L

0   125   250   500

FEET

Existing S-1
Treatment System

begin in the spring of 1999. The cessation of engineered remedial activities was assumed to occur at the end of year 2002.

Figures 6.1 and 6.2 compare CB concentrations at the beginning and end of the first year of source removal actions. The groundwater model predicts that initial source removal actions would result in proportional concentration decreases in the source area of the groundwater plume. For instance, assumed source removal rates ranging from 53 to 90 percent in the first year caused comparable reductions in dissolved CB concentrations in the source area. Table 6.2 summarizes simulated groundwater CB concentrations at selected well locations for each year. However, downgradient CB concentrations were not achieved in the first year of source remediation. The groundwater CB plume continued to extend 2,000 feet beyond the source area at concentrations of 10 µg/L or greater.

Figure 6.3 illustrates the predicted groundwater plume 5 years after the initiation of engineer source area remediation, or calendar year 2004. By this time, the effects of source remediation are evident throughout the length of the CB plume, and dissolved CB concentrations are one to two orders of magnitude below the 1999 concentrations at most locations. In addition, the CB plume begins to narrow and recede at the downgradient edge; the length of the groundwater plume is approximately 1,900 feet from the source area. CB concentrations up to 35 µg/L are predicted to remain at monitoring well SS003MW016 by calendar year 2004, and concentrations in excess of 100 µg/L are predicted to migrate 1,000 feet past the Base boundary. Although the CB plume is predicted to maintain its original shape, CB concentrations at all locations in the groundwater plume are not predicted to exceed 1,000 µg/L by 2004.

Figures 6.4 and 6.5 are predictions of CB plume magnitude and extent for calendar years 2009 and 2019 (6 and 16 years after the cessation of assumed excavation and SVE activities). By calendar year 2009, the CB plume extends only 1,500 feet beyond the source area (at concentrations of 10 µg/L or above). However, CB concentrations above the Texas Risk Reduction Standard 2 value of 100 µg/L continue to migrate 200 feet north of the Base boundary. Twenty years after the initiation of source area remediation activities (calendar year 2019; Figure 6.5), the groundwater plume is predicted to have retreated to one-half of its original length, and CB concentrations in the source area are below 500 µg/L. The numerical model predicts that CB concentrations of 100 µg/L will continue to migrate up to 200 feet north of the Base boundary. CB concentrations are predicted to decrease below 100 µg/L at all off-base monitoring wells (primarily monitoring well SS003MW001) by calendar year 2035 (figure not shown), or 36 years after the initiation of engineered source remediation.

As indicated by the groundwater model, the close proximity of the former sump area to the Base boundary and high groundwater velocities beneath the sump area will continued to result in detectable off-base concentrations of CB, even if significant source reduction efforts are made. The calibrated model predicts that 36 years will be required after initiation of source remediation activities before CB concentrations at all off-base wells are below 100 µg/L. The predicted maximum groundwater CB concentration in the former source area in 2035 is below 320 µg/L, and leaching of CB from LNAPL into the groundwater is assumed to be reduced by more than 98 percent.

TABLE 6.2
SUMMARY OF MODELED CHLOROBENZENE CONCENTRATIONS
SITE S-1 MNA TS
KELLY AIR FORCE BASE, TEXAS

Monitoring Well	Calibrated Plume	Predicted CB Concentrations (micrograms per liter)					
		1999	2000	2004	2009	2019	2035
SS003MW050	18180	18600	9120	870	705	518	289
SS003MW272	47360	43810	8530	551	480	394	203
SS003MW121	14140	13190	5730	515	420	397	197
SS003MW273	21320	22780	10670	890	740	608	320
SS003MW110	11330	13930	6500	512	470	356	189
SS003MW001	6500	4000	3800	380	210	190	96
SS003MW010	530	474	443	306	20	14	3
SS003MW016	46	43	39	35	8	<1	<1

The magnitude of CB biodegradation at Site S-1 will increase in the future, resulting in more rapid attainments of Texas Risk Reduction Standard 2 values at all off-base locations. Conceptually, several factors at Site S-1 will promote accelerated losses of CB contamination. First, aerobic biodegradation of CB should become more important with time as the ratio of dissolved organic carbon per unit mass of DO decreases through remediation and weathering. The physical effects of such a trend would be observed as increasing DO concentrations across the site and a corresponding accelerated retreat of the CB plume. Secondly, natural weathering rates may exceed the assumed model rate of 3 percent per year. As mentioned in Section 6.2.1, weathering rates are governed by several dynamic factors at the site, including the effective aqueous solubility of CB (and other LNAPL components), groundwater velocity, LNAPL-water contact area, and the molecular diffusivity, none of which can be estimated with a high degree of accuracy. In addition, SVE may temporarily promote the oxygenation of groundwater as a result of increased air flow through the vadose zone and diffusion into the groundwater, resulting in higher CB biodegradation rates during SVE system operation.

Overall, the groundwater model predicts that exposure pathways involving shallow groundwater are not complete under current conditions, nor will the CB plume expand to impact potential downgradient receptors under worst-case conditions. Calibrated model Kelly-B presented in Section 5, simulated the migration of the CB plume under more conservative conditions than used in the above-derived simulations. For instance, model Kelly-B was calibrated to more closely match the 1989 CB plume, which was longer than the plume observed more recently (1995 to 1998) and had a relatively high CB concentration (610 µg/L) at monitoring well SS003MW016. The biodegradation rate in model Kelly-B was lower than used in model Kelly-A (1.3×10^{-3} day^{-1}). CB concentrations simulated by model Kelly-B extended a maximum of 2,900 feet from the edge of the former sump area. The downgradient extent of the plume toe was over 1 mile from the nearest surface water body (Apache Creek). The results of this model indicate that, even if remedial activities other than MNA are not implemented at Site S-1, the groundwater plume is not anticipated to impact any downgradient receptors; however, the predicted remediation times would be much longer than if engineered source reduction were implemented.

Model Kelly-C was used to explore the possibility that plume attenuation is more significant based on observed CB plume sizes since December 1995. Model Kelly-C simulated the average CB plume length observed since December 1995, whereas model Kelly-A used the maximum CB plume length observed in March/April 1998. Therefore, the calibrated model Kelly-C was 300 feet shorter than calibrated model Kelly-A. The results of model Kelly-C are fully summarized in Appendix F. The results indicate that if model Kelly-C is more representative of current groundwater CB contamination, then the combination of source removal and natural attenuation will result in the attainment of the groundwater remediation goal for CB (100 µg/L) at least 5 years sooner than predicted by model Kelly-A.

Groundwater modeling indicates that CB contamination above 100 µg/L likely will remain off-base nearest the base boundary for at least a decade. Therefore, promulgated, single-point remediation goals may be developed as part of the CMS to protect off-base groundwater resources; however, institutional controls will likely be placed on

groundwater use within the remediation zone at Site S-1 (on and off base) to prevent completion of existing pathways until remediation is complete. Part of the implementation of institutional controls during site remediation will involve monitoring the progress of plume remediation and verification of the groundwater model. The details of long-term groundwater monitoring are described in the following sections.

6.3 LONG-TERM GROUNDWATER MONITORING

A proposed long-term groundwater monitoring plan was developed on the basis of groundwater sampling results and the numerical model. This LTM plan identifies the locations of two groundwater monitoring networks and develops a groundwater sampling and analysis strategy to demonstrate the effectiveness of MNA at off-base locations. The strategy described in this section is designed to monitor plume migration over time and to verify that MNA is occurring at rates sufficient to protect potential receptors. Prior to implementation of the plan, any available interim groundwater results should be evaluated to refine the placement of additional groundwater monitoring wells, if needed. In the event that data collected under the LTM program indicate that natural processes are insufficient to protect human health and the environment, contingency controls to augment the beneficial effects of MNA would be necessary.

Two separate sets of wells will be utilized at the site as part of the MNA with LTM remedial alternative. The first set will consist of 9 LTM wells located in, upgradient, and downgradient from the observed contaminant plume to verify model predictions that natural attenuation is occurring at rates sufficient to minimize plume expansion and reduce CB concentrations.

The second set of wells will consist of 3 POC wells located along a line perpendicular to the general direction of groundwater flow and approximately 750 feet northeast of monitoring well SS003MW016. The purpose of the POC wells is to verify that no CB concentrations exceeding state groundwater criteria migrate beyond the area under institutional control. The proposed POC well locations are designed to allow sufficient warning time in the event that remedial activities were not performed at Site S-1, or were to achieve a lower cleanup effectiveness than predicted.

6.3.1 Long-Term Monitoring Wells

At eight locations, groundwater wells within, upgradient, crossgradient, and downgradient from the current CB plume will be used to monitor the effectiveness of MNA in reducing total contaminant mass and minimizing contaminant migration at Site S-1. Groundwater conditions upgradient from the plume will be monitored at well SS003MW275. Wells SS003MW272 and SS003MW273 will be used to monitor conditions in the source area and within the most reducing portion of the treatment zone. Wells SS003MW001, SS003MW011, and SS003MW010 are proposed for monitoring the CB concentrations along the centerline of the downgradient plume extending to the plume boundary. Monitoring wells SSS003MW009 and SS003MW013 are proposed to monitor the width of the groundwater plume and any potential expansion. Figure 6.6 identifies the proposed locations of the wells to be used

LEGEND

✛ MONITORING WELL LOCATION

➤ GROUNDWATER FLOW DIRECTION

◯ APPROXIMATE LIMIT OF FORMER
    TOPOGRAPHIC DEPRESSION AREA

(LTM) PROPOSED LONG-TERM
       MONITORING WELL LOCATION

✛ PROPOSED POINT-OF-COMPLIANCE
    WELL LOCATION

—10— LINE OF EQUAL CB CONCENTRATION
      (MARCH/APRIL 1998 DATA)

0   125   250   500
        FEET

Existing S-1
Treatment System

for LTM. This network will supplement the POC wells to provide evidence of continuing MNA and to allow additional response time if site conditions deteriorate.

6.3.2 Point-of-Compliance Wells

Three POC monitoring wells are proposed for installation in a row perpendicular to plume migration and centered on monitoring well SS003MW016. Figure 6.6 shows the proposed locations of the POC wells. The purpose of the POC wells is to verify that no contaminated groundwater exceeding regulatory criteria migrates beyond these locations. Although available evidence strongly suggests that the contaminant plume will not migrate beyond this area at concentrations exceeding chemical-specific state groundwater standards, these POC wells are the technical mechanisms used to demonstrate protection of human health and the environment and compliance with regulatory criteria. These wells will be installed and monitored to assure that MNA is providing the anticipated level of risk reduction and remediation at the site.

6.4 GROUNDWATER SAMPLING

To ensure that sufficient contaminant removal is occurring at Site S-1 to meet site-specific remediation goals, the long-term groundwater monitoring plan includes a sampling and analysis plan. Groundwater samples will be collected annually from LTM wells to verify that naturally occurring processes are effectively reducing the mass and mobility of CB contamination. The sampling and analysis plan also is aimed at confirming that MNA can achieve site-specific remediation concentration goals for CB that are protective of human health and the environment.

6.4.1 Sampling Frequency

Each of the LTM and POC wells should initially be sampled annually for 11 years (1999 to 2009) and biennially (every other year) for the next 10 years (2010 to 2019). If the data collected during this time period support the anticipated effectiveness of the MNA alternative at this site, the sampling frequency could be reduced, or sampling could be eliminated. If the data collected at any time during the monitoring period indicate the need for additional remedial activities at the site, the sampling frequency should be adjusted accordingly. Likewise, if the data indicate that the dissolved plume has been remediated to below 100 µg/L of CB throughout its entire areal extent, LTM could be discontinued.

6.4.2 Long-Term Monitoring Cost

The present-worth cost of implementing a LTM program beginning in 1999 is summarized in Table 6.3. Included in the total present-worth cost of $168,230 are the estimated costs for installing additional POC wells, performing the recommended groundwater monitoring, maintaining institutional controls, public education, project management, and reporting. Yearly natural attenuation sampling and results reporting for a total of 11 LTM and POC wells is anticipated to cost $14,410. Cost calculations are contained in Appendix E.

TABLE 6.3
ESTIMATED LTM COSTS
SITE S-1 MNA TS
KELLY AIR FORCE BASE, TEXAS

Capital Costs	Present Worth Cost
Design/construct two POC wells in 1999	$7,860

Monitoring Costs	Present Worth Cost
Conduct annual groundwater monitoring from 1999 to 2009	$70,500
Conduct biennial groundwater monitoring from 2010 to 2019	$24,860
Site management (maintain institutional controls/public education) (1999 to 2019)	$65,010
Total Present Worth of Alternative 1 [a/]	**$168,230**

[a/] Based on an annual adjustment factor of 7 percent.

Note: Costs assume that well installation and LTM are performed by local (San Antonio) personnel.

6.4.3 Analytical Protocol

All LTM and POC wells in the LTM program will be sampled and analyzed to determine compliance with chemical-specific remediation goals and to verify the effectiveness of MNA at the site. At the beginning of each annual sampling event, water levels will be measured at all site monitoring wells. Groundwater samples will be analyzed for the parameters listed in Tables 6.4 and 6.5. A site-specific groundwater sampling and analysis plan should be prepared prior to initiating this LTM program.

TABLE 6.4
LONG-TERM GROUNDWATER MONITORING ANALYTICAL PROTOCOL
SITE S-1 MNA TS
KELLY AIR FORCE BASE, TEXAS

Analyte	Method/Reference	Comments	Data Use	Recommended Frequency of Analysis	Sample Volume, Sample Container, Sample Preservation	Field or Fixed-Base Laboratory
Ferrous Iron (Fe^{2+})	Colorimetric A3500-Fe D or Hach 25140-25	Filter if turbid	May indicate an anaerobic degradation process due to the depletion of oxygen, nitrate, and manganese	Each sampling event	Collect 100 mL of water in a glass container; for Method A3500-FeD, acidify with hydrochloric acid per method	Field
Temperature	E170.1, direct-reading meter	Measure at well-head	Purging adequacy; metabolism rates for microorganisms depend on temperature	Each sampling event	Measure at well-head using a flow-through cell	Field
Dissolved Oxygen	Dissolved oxygen meter	Measure at well-head; refer to Method A4500 for a comparable laboratory procedure	Purging adequacy; concentrations less than 1 mg/L generally indicate an anaerobic pathway	Each sampling event	Measure at well-head using a flow-through cell	Field
pH	E150.1/SW9040, direct-reading meter	Measure at well-head	Purging adequacy; aerobic and anaerobic processes are pH-sensitive	Each sampling event	Measure at well-head using a flow-through cell	Field
Conductivity	E120.1/SW9050, direct-reading meter	Measure at well-head	General water quality parameter used as a marker to verify that site samples are obtained from the same groundwater system	Each sampling event	Collect 100–250 mL of water in a glass or plastic container or measure at wellhead using flow-through cell	Field
Nitrate (NO_3^{-1})	IC method E300 or method SW9056; colorimetric, method E353.2	Method E300 is a Handbook[a] method; method SW9056 is an equivalent procedure	Substrate for microbial respiration if oxygen is depleted	Each sampling event	Collect up to 40 mL of water in a glass or plastic container; cool to 4°C; analyze within 48 hours	Fixed-base

TABLE 6.4 (Concluded)
LONG-TERM GROUNDWATER MONITORING ANALYTICAL PROTOCOL
OU4 RNA TS
SHAW AFB, SOUTH CAROLINA

Analyte	Method/Reference	Comments	Data Use	Recommended Frequency of Analysis	Sample Volume, Sample Container, Sample Preservation	Field or Fixed-Base Laboratory
Sulfate (SO$_4$$^{2-}$)	IC method E300 or method SW9056 or Hach SulfaVer 4 method	Method E300 is a Handbook method; method SW9056 is an equivalent procedure. Hach method is Photometric	Substrate for anaerobic microbial respiration	Each sampling event	Collect up to 40 mL of water in a glass or plastic container; cool to 4°C	Fixed-base or field (for Hach method)
Oxidation-Reduction Potential (ORP)	A2580 B, direct-reading meter	Measurements are made with electrodes; results are displayed on a meter; samples should be protected from exposure to atmospheric oxygen	The redox potential of groundwater influences and is influenced by biologically mediated reactions; the redox potential of groundwater may range from more than 200 mV to less than -400 mV	Each sampling event	Measure at well-head using a flow-through cell	Field
Methane	RSKSOP-114 modified to analyze water samples for methane by headspace sampling with dual thermal conductivity and flame ionization detection.	Method published and used by the USEPA National Risk Management Research Laboratory	The presence of methane indicates the presence of sufficiently reducing conditions for reductive detalogenation to occur	Each sampling event	Collect water samples in 40 mL volatile organic analysis (VOA) vials with butyl gray/Teflon-lined caps (zero headspace); cool to 4°C	Fixed-base
Aromatic Volatile Organics	GC/MS method SW8260B or GC method SW8021B.	SW8260 is the Handbook method.	Measured for regulatory compliance.	Each sampling event	Collect water samples in a 40 mL VOA vial; cool to 4°C; add hydrochloric acid to pH < 2	Fixed-base

a/ Handbook refers to the AFCEE (1993) "Handbook for the Installation Restoration Program (IRP) Remedial Investigations and Feasibility Studies (RI/FS)."

TABLE 6.5
POINT-OF-COMPLIANCE GROUNDWATER MONITORING ANALYTICAL PROTOCOL
SITE S-1 MNA TS
KELLY AIR FORCE BASE, TEXAS

Analyte	Method/Reference	Comments	Data Use	Recommended Frequency of Analysis	Sample Volume, Sample Container, Sample Preservation	Field or Fixed-Base Laboratory
Temperature	E170.1	Field only	Well development	Each sampling event.	N/A	Field
Dissolved Oxygen	Dissolved oxygen meter	Refer to method A4500 for a comparable laboratory procedure.	The oxygen concentration is an indicator of biodegradation conditions; concentrations less than 1 mg/L generally indicate an anaerobic pathway.	Each sampling event.	Collect 300 mL of water in biochemical oxygen demand bottles; analyze immediately; alternately, measure dissolved oxygen in situ.	Field
pH	E150.1/SW9040, direct-reading meter	Protocol/Handbook methods[a]	Aerobic and anaerobic processes are pH-sensitive.	Each sampling event.	Collect 100–250 mL of water in a glass or plastic container; analyze immediately.	Field
Conductivity	E120.1/SW9050, direct-reading meter	Protocol/Handbook methods	General water quality parameter used as a marker to verify that site samples are obtained from the same groundwater system.	Each sampling event.	Collect 100–250 mL of water in a glass or plastic container.	Field
Aromatic Volatile Organics	GC/MS method SW8260B or GC method SW8021B.	SW8260 is the Handbook method.	Measured for regulatory compliance.	Each sampling event.	Collect water samples in a 40 mL VOA vial; cool to 4°C; add hydrochloric acid to pH < 2.	Fixed-base

[a] Protocol methods are presented by Wiedemeier *et al.* (1995).

TABLE 6.5
POINT-OF-COMPLIANCE GROUNDWATER MONITORING ANALYTICAL PROTOCOL
SITE S-1 MNATS
KELLY AIR FORCE BASE, TEXAS

Analyte	Method/Reference	Comments	Data Use	Recommended Frequency of Analysis	Sample Volume, Sample Container, Sample Preservation	Field or Fixed-Base Laboratory
Temperature	E170.1	Field only	Well development	Each sampling event.	N/A	Field
Dissolved Oxygen	Dissolved oxygen meter	Refer to method A4500 for a comparable laboratory procedure.	The oxygen concentration is an indicator of biodegradation conditions; concentrations less than 1 mg/L generally indicate an anaerobic pathway.	Each sampling event.	Collect 300 mL of water in biochemical oxygen demand bottles; analyze immediately; alternately, measure dissolved oxygen in situ.	Field
pH	E150.1/SW9040, direct-reading meter	Protocol/Handbook methods[a/]	Aerobic and anaerobic processes are pH-sensitive.	Each sampling event.	Collect 100–250 mL of water in a glass or plastic container; analyze immediately.	Field
Conductivity	E120.1/SW9050, direct-reading meter	Protocol/Handbook methods	General water quality parameter used as a marker to verify that site samples are obtained from the same groundwater system.	Each sampling event.	Collect 100–250 mL of water in a glass or plastic container.	Field
Aromatic Volatile Organics	GC/MS method SW8260B or GC method SW8021B.	SW8260 is the Handbook method.	Measured for regulatory compliance.	Each sampling event.	Collect water samples in a 40 mL VOA vial; cool to 4°C; add hydrochloric acid to pH < 2.	Fixed-base

a/ Protocol methods are presented by Wiedemeier et al. (1995).

TABLE 6.5
POINT-OF-COMPLIANCE GROUNDWATER MONITORING ANALYTICAL PROTOCOL
SITE S-1 MNA TS
KELLY AIR FORCE BASE, TEXAS

Analyte	Method/Reference	Comments	Data Use	Recommended Frequency of Analysis	Sample Volume, Sample Container, Sample Preservation	Field or Fixed-Base Laboratory
Temperature	E170.1	Field only	Well development	Each sampling event.	N/A	Field
Dissolved Oxygen	Dissolved oxygen meter	Refer to method A4500 for a comparable laboratory procedure.	The oxygen concentration is an indicator of biodegradation conditions; concentrations less than 1 mg/L generally indicate an anaerobic pathway.	Each sampling event.	Collect 300 mL of water in biochemical oxygen demand bottles: analyze immediately; alternately, measure dissolved oxygen in situ.	Field
pH	E150.1/SW9040, direct-reading meter	Protocol/Handbook methods[a/]	Aerobic and anaerobic processes are pH-sensitive.	Each sampling event.	Collect 100–250 mL of water in a glass or plastic container; analyze immediately.	Field
Conductivity	E120.1/SW9050, direct-reading meter	Protocol/Handbook methods	General water quality parameter used as a marker to verify that site samples are obtained from the same groundwater system.	Each sampling event.	Collect 100–250 mL of water in a glass or plastic container.	Field
Aromatic Volatile Organics	GC/MS method SW8260B or GC method SW8021B.	SW8260 is the Handbook method.	Measured for regulatory compliance.	Each sampling event.	Collect water samples in a 40 mL VOA vial; cool to 4°C; add hydrochloric acid to pH < 2.	Fixed-base

a/ Protocol methods are presented by Wiedemeier *et al.* (1995).

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

This report presents the results of a TS conducted to evaluate the use of natural attenuation for remediation of CB-contaminated groundwater at Site S-1, Kelly AFB, Texas. The finite-difference model Bioplume III was used in conjunction with site-specific geologic, hydrologic, and laboratory analytical data to simulate the migration and biodegradation of CB dissolved in groundwater. To obtain the data necessary for the MNA demonstration, soil and groundwater samples were collected from the site and analyzed. Physical and chemical data collected under this program were supplemented (where necessary) with data collected during previous site characterization events.

Organic contaminants detected in groundwater as part of this study included fuel hydrocarbons, chlorinated ethenes, and chlorinated benzene compounds. With the exception of benzene and naphthalene, concentrations of all fuel hydrocarbon compounds detected at the site were below 30 µg/L. Benzene and naphthalene were detected at maximum concentrations of 4,100 and 170 µg/L, respectively. Only trace concentrations of PCE, TCE, and DCE were present in the source area at Site S-1, whereas, higher concentrations of these compounds were detected to the north and southwest of the main contaminant plume. The maximum observed chlorinated ethene concentration during this study was 190 µg/L of PCE at well SS003MW013 north of the existing contaminant plume. This study confirmed that the groundwater CB plume is the most extensive contaminant plume at the Site S-1; CB was measured at a maximum concentration of 45,000 µg/L. Other chlorinated benzene compounds present at Site S-1 included 1,2,4-TCB and all three DCB isomers. TCB was present at concentrations below 24 µg/L, and individual DCB isomer concentrations were below 10,000 µg/L.

Comparison of contaminant, electron acceptor, and biodegradation byproduct isopleth maps for Site S-1 provides strong qualitative evidence of biodegradation of dissolved contaminants. These geochemical data indicate that substantial aerobic biodegradation of contaminants has occurred and DO concentrations within and downgradient of the Site S-1 source area are depleted. Aerobic microcosm study data collected for the site indicates that a viable population of CB-degrading microorganisms is present. The results of these microcosm studies indicate that aerobic CB biodegradation at Site S-1 is slowed only by the rate at which oxygen can be resupplied to the aquifer. Groundwater CB contamination measured in this study has migrated under anaerobic conditions up to 2,000 feet from the source area. Field-scale, first-order CB decay rates computed using data from Site S-1 range from 7.9×10^{-4} to 1.9×10^{-2} day^{-1}.

Additional geochemical indicator data strongly suggest that reductive dechlorination of dissolved TCB, DCB, TCE, and DCE is occurring at the site as capable microbes utilize natural organic carbon, BTEX, and other fuel hydrocarbons as substrates. Contaminants

known to be susceptible to reductive dechlorination are generally degraded prior to off-base migration. Field-scale, first-order decay rates for DCB were estimated to range from 4.6×10^{-3} day^{-1} to 6.7×10^{-2} day^{-1}.

An important component of this study was an assessment of the potential for contamination in groundwater to migrate from the source areas to potential receptor exposure points (i.e., surface water bodies or extraction wells downgradient from the source). Bioplume III simulations were used to predict CB migration under the effects of natural attenuation and engineered remedial activities proposed as part of the FS process. Anticipated source removal activities at Site S-1 that were accounted for by the Bioplume III model included limited source area excavation and subsequent SVE of remaining residual and mobile LNAPL in the source area. During model calibration, model parameters that could not be obtained from existing site data were estimated using common literature values for aquifer materials similar to those found at the site.

The model used to simulate CB degradation (Kelly-A) incorporates the assumption that dissolution from mobile and/or residual NAPL in the source area into groundwater is significantly decreased due to source excavation and SVE over a four year period. Source area concentrations in the model representing LNAPL contamination at the site were decreased by 53 to 90 percent within the first year of modeled remedial activities. After 4 years of source treatment, the leachable LNAPL mass at Site S-1 was assumed to be reduced by at least 90 percent. Natural source weathering after remediation was assumed to occur at a geometric rate of 3 percent per year during the remaining predictive period.

The results of model Kelly-A indicate that the effects of natural attenuation currently stabilize the CB plume. Future weathering and remediation of the source area will enhance the rate of CB concentration decrease and plume retreat. Although modeled CB concentrations are predicted to be greatly diminished as a result of source remediation activities, the groundwater model predicts that CB concentrations above the Texas Risk Reduction Standard 2 value of 100 µg/L may remain until calendar year 2035 (assumes source remediation begins in 1999 and continues for 4 years) at wells closest to the perimeter of the Base. CB concentrations at all other downgradient wells more distant from the Base perimeter are predicted to drop below 100 µg/L much more rapidly. Groundwater data suggest that the CB plume currently may have stabilized at a length at least 300 feet shorter than predicted by model Kelly-A. If so, the length of time needed to achieve groundwater remediation standards at Site S-1 is shortened by a minimum of 5 years (model Kelly-C). If source remediation activities are not conducted at Site S-1, the estimated time for the attainment of regulatory levels at all off-base wells is anticipated to exceed model predictions by decades.

To assess the effectiveness of both naturally-occurring processes and future engineered source reduction at reducing contaminant mass and minimizing contaminant migration, groundwater from a minimum of 8 existing monitoring wells and 3 proposed monitoring wells should be sampled annually for 11 years to build a historical groundwater quality database for the site. Following completion of the 10-year annual LTM period, the LTM program should be reassessed. If the annual sampling results indicate that temporal changes in plume magnitude and extent could be adequately monitored by less-frequent sampling events, then the frequency of LTM could be reduced appropriately. The number and location of wells selected for continued monitoring should be determined on the basis of results from the initial, 10-year LTM period.

The LTM plan should be periodically reviewed and revised as appropriate on the basis of available groundwater quality data. For example, if sampling results demonstrate that the plume is in equilibrium (not receding or migrating downgradient) or is receding toward the source area, then the sampling frequency could be reduced appropriately. If the data collected at any time during the monitoring period indicate the need for additional remedial activities at the site, sampling frequency should be adjusted accordingly and the appropriate remedial actions, such as aggressive pump-and-treat operations, should be evaluated and implemented.

SECTION 8

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APPENDIX F

ADDITIONAL GROUNDWATER MODELING

The purpose of Appendix F is to document the calibration and use of an additional groundwater model constructed for Site S-1 that incorporates different modeling assumptions than used in models Kelly-A or Kelly-B (Sections 5 and 6). Model Kelly-C was developed to explore possible future migration of the groundwater CB plume at Site S-1 under less conservative site conditions than assumed for models Kelly-A or Kelly-B. The calibration and predictions of model Kelly-C are discussed in the following sections.

F.1 BACKGROUND INFORMATION

The fate and transport assessment in Sections 5 and 6 incorporated several conservative assumptions about physical and chemical parameters at Site S-1. The use of parameter assumptions in groundwater modeling is necessary to provide a conceptual framework for the model and to aid in model calibration. Calibration of the contaminant transport model is essential to demonstrate that contaminant transport conditions are being accurately simulated at Site S-1. Conservative parameter estimation is one modeling technique used to provide a safety factor for model predictions given the uncertainty regarding the actual values of input parameters throughout the model domain (e.g., in the event that unforeseen future changes in site conditions cause the rate of leaching of contaminant mass to the aquifer to increase, thereby enlarging the contaminant plume). Without a reasonable degree of conservative parameter estimation, naturally fluctuating contaminant concentrations, recharge rates, or other such highly variable physical or chemical features of a site can cause a groundwater model to predict premature plume retreat.

Groundwater CB data collected between September 1994 and June 1998 were used to calibrate model Kelly-A (Section 5). Table 5.2 listed final calibrated CB concentrations for model Kelly-A versus observed CB concentrations at the selected calibration wells. A total of five source and three downgradient monitoring wells were used as calibration wells. The calibration wells were divided into two zones, including source wells within the former sump area, and downgradient wells north/northeast of the base boundary.

Maximum groundwater CB concentrations measured in the source area at Site S-1 were used as conservative calibration target concentrations for model Kelly-A. The use of maximum groundwater CB concentrations (monitoring wells SS003MW050, SS003MW272, SS003MW121, SS003MW273) was based on the observation that groundwater CB data at these source wells did not increase or decrease significantly

between September 1994 and June 1998 (the oldest available groundwater CB data from the source area was collected in September 1994). Therefore, the use of maximum CB concentrations in the source area as calibration targets is reasonably conservative.

The groundwater CB calibration targets at downgradient wells (SS003MW001, SS003MW010, and SS003MW016) for model Kelly-A were the maximum concentrations observed between March 1997 and June 1998. The available data set for downgradient monitoring wells spans the years 1990 to 1998 (Table 4.5: Appendix A); however, the groundwater data set is discontinuous. For instance, a five-year data gap (1990 to 1995) exists for monitoring wells SS003MW001, SS003MW010, and SS003MW016, followed by a 2-year data gap (1995 to 1997) for monitoring well SS003MW016. A review of groundwater CB concentrations suggests that downgradient CB concentrations generally are decreasing. For instance, groundwater CB concentrations at monitoring well SS003MW016 have decreased from 610 µg/L in November 1989 to 1 µg/L in June 1998. The lack of CB detections at SS003MW016 during multiple sampling events between November 1997 and June 1998 suggests that the groundwater CB plume at Site S-1 is receding.

The gap in groundwater data between 1990 and 1995, and the installation of the groundwater extraction system at Site S-1 in March 1995, both add to the uncertainty regarding the influence of natural attenuation processes on the CB plume. The observed recession of the CB plume may not be the sole result of natural groundwater attenuation and source weathering. Groundwater data collected in 1995 was obtained after the pump and treat system had been operational for at least 6 months, and it is possible that pump and treat operations are reducing the plume length. If so, the groundwater CB plume may migrate to the length observed in March 1998 if pump and treat operations are terminated. Furthermore, seasonally high rainfall rates may contribute to enhanced source leaching and subsequent plume extension, or plume contraction if rainfall rates are low. Base negotiations with the TNRCC will determine if groundwater pump and treat operations will be discontinued within a reasonable time frame after initiation of source area remediation efforts. Model Kelly-A assumed that groundwater pump and treat activities would be continued for one year beyond the initiation of source treatment activities.

If pump and treat activities at Site S-1 are continued until dissolved contaminant concentrations are decreased below prescribed clean-up criteria, then the modeling assumptions incorporated into model Kelly-A are conservative (the simulated CB plume would likely be larger than the actual plume). Furthermore, groundwater CB contamination predicted by model Kelly-A is higher than observed in recent years. Therefore, model Kelly-C was calibrated to a smaller plume size than used in model Kelly-A. Model Kelly-C explores the possibility that permanent plume attenuation has occurred and that the length of the plume observed in March/April 1998 was anomalous. The techniques used for this calibration process is described in the following sections.

F.2 MODEL KELLY-C OBJECTIVES

Model Kelly-C was calibrated with the assumption that a permanent retreat of the groundwater plume has occurred at Site S-1. Specifically, the model was calibrated to simulate a CB concentration of 16 µg/L at well SS003MW016 (average CB concentrations measured between December 1995 and June 1998). In contrast, model Kelly-A was calibrated to a concentration of 49 µg/L in this well (measured in March 1998). Model Kelly-C assumes that the March 1998 concentration was anomalous and not representative of average plume conditions. The reduction of the CB calibration target at well SS003MW016 from 49 µg/L to 16 µg/L shortened the calibrated CB plume length by 300 feet.

F.3 SETUP AND CALIBRATION OF MODEL KELLY-C

The configuration of the CB plume used to guide the calibration of model Kelly-C is identical to that illustrated in Figure 4.9, with the exception that the CB concentration at monitoring well SS003MW016 was assumed to be 16 µg/L versus 49 µg/L . Other CB concentrations in the source area and along the plume centerline were assumed to be the same as shown in Figure 4.9. The following input parameters were altered to create model Kelly-C: 1) first-order biodegradation rate; 2) retardation rate; and 3) source leaching rates.

F.3.1 Adjustment of First-Order Biodegradation Rate

The first-order biodegradation rate in Model Kelly-C was set at 3.1×10^{-3} day^{-1} versus 2.7×10^{-3} day^{-1} in Model Kelly-A. This small change in the biodegradation rate helped achieve a decrease in plume length and facilitated simulation of the desired calibration concentration at well SS003MW016, and falls within the range of biodegradation rates computed for the site (Section 4.7).

F.3.2 Adjustment of Retardation Rate

The retardation rate of 1.36 in model Kelly-A was increased to 1.52. The alteration of the retardation rate decreased the velocity of contamination migration. Because contaminant migration velocities were lowered, more CB biodegradation would occur prior to downgradient migration, resulting in a shortening of the plume.

F.3.3 Adjustment of Source Leaching Rates

Source leaching rates were increased to maintain observed maximum dissolved CB concentrations in the Site S-1 source area.

F.4 MODEL CALIBRATION RESULTS

The size of the calibrated CB plume simulated by model Kelly-C based on the 10 µg/L contour (Figure F-1) closely matches the size of the observed groundwater CB plume in

March/April 1998 (Figure 4.9). The most noticeable difference is that the calibrated plume is 300 feet shorter than the calibrated plume simulated by model Kelly-A (Figure 5.7). CB concentrations in several source area wells resembled measured concentrations more closely than with model Kelly-A (wells SS003MW272, SS003MW272, and SS003MW110). The highest observed CB concentration of 45,000 µg/L in the source area was closely approximated by model Kelly-C (45,860 µg/L). Other source area concentrations were within 10 percent of the observed value.

Similar to Model Kelly-A, calibrated CB concentrations in model Kelly-C at downgradient wells were conservative with respected to observed CB concentrations (Table F.1). The size of the model grid cells limited the resolution of the model calibrations and precise simulation of measured CB concentrations could not be achieved at every point. However, a calibrated CB concentration of 14 µg/L was attained at monitoring well SS003MW016, thereby achieving the primary model calibration objective of establishing a shorter groundwater plume.

F.5 APPICATION OF MODEL KELLY-C TO SITE S-1

The modeling assumptions used to predict CB plume migration trends for Kelly-A were repeated for model Kelly-C (see Section 6.2.1). It was assumed that part of the source area would be excavated, and that the remaining residual soil contamination would be treated by SVE for a period of 4 years. Model predictions for models Kelly-A and Kelly-C were similar. Figures F.2 to F.4 present the results of model Kelly-C for selected years between 2004 and 2019. Table F.2 lists individual modeled CB concentrations at selected monitoring wells. As in model Kelly-A, source remediation is predicted to substantially reduce CB concentrations in the former sump area and along the centerline of the CB plume within the five-year period after the start of source remediation.

Between calendar years 2004 and 2009, the groundwater plume is predicted to recede by approximately one-third. By calendar year 2009, CB concentrations above the TNRCC action level of 100 µg/L are predicted to persist in a 1.2-acre area near the base boundary. The plume area exceeding 100 µg/L is predicted to recede below 1 acre by 2019. CB concentrations are not predicted to decrease below 100 µg/L at any location off-Base prior to calendar 2030, or 31 years after the initiation of engineered source remediation.

Although model Kelly-C implemented a relatively liberal interpretation of the actual CB plume length as compared to model Kelly-A, the predictive results of the two models are very similar. Both models indicate the potential for off-Base CB concentrations above 100 µg/L to persist for several decades. However, both groundwater models indicate that CB contamination at Site S-1 will not migrate farther than 1,125 feet downgradient from the base boundary at concentrations above 100 µg/L.

The accuracy of the Bioplume III model predictions will be determined by their ability to accurately predict anticipated source remediation efforts. Source remediation rates that exceed those assumed for Models Kelly-A and Kelly-C will result in an accelerated rate of plume remediation compared to model predictions. Furthermore, as contaminant mass is

removed from the groundwater system, the ratio of oxygen to carbon will increase. This increase in the oxygen-to-carbon ratio will result in faster rates of CB removal (e.g., faster biodegradation rates) because CB is very susceptible to aerobic biodegradation. Bioplume III is limited to the use of a single first-order biodegradation rate that cannot be changed as more electron acceptors become available.

F.6 VARIATION OF BIODEGRADATION RATES

As stated in Section F.3.1, an average biodegradation rate of 3.1×10^{-3} day^{-1} was used for model Kelly-C. However, calculated CB biodegradation rates at Site S-1 varied from 1.9×10^{-2} day^{-1} to 7.9×10^{-4} day^{-1}. The one-and-a-half order of magnitude difference in calculated biodegradation rates is due to several factors: 1) rapid groundwater velocities in the source area (estimated to be approximately 5 feet per day) compared to beneath the residential area (approximately 0.5 feet per day) cause the rates of oxygen supply to the aquifer near the source area to be more rapid than in more downgradient areas; 2) the operation of the groundwater pump-and-treat system removes contaminant mass from the aquifer; and 3) the presence of a large anaerobic zone downgradient from the source area slows the natural attenuation of the CB plume. These factors indicate that the application of an average biodegradation rate to model Kelly-C would underestimate biodegradation rates from the source area and overestimate biodegradation rates downgradient of the source area.

The maximum and minimum calculated biodegradation rates were applied to model Kelly-C to observe the effects that these rates have on future plume migration. Other model parameters were not modified. Once the biodegradation rate was adjusted, the resulting model-predicted plume was compared to the plume simulated using a decay rate of 3.1×10^{-3} day^{-1}. The results of these additional model simulations are listed in Tables F.3 and F.4, and can be compared to the model results for Kelly-C listed in Table F.2. The process of changing the biodegradation rate was identical to the sensitivity analysis process for model Kelly-A described in Section 5.5.

The results of the sensitivity analysis described in Section 5.5.6 indicated that the calibrated Kelly-A model was reasonable. These results indicated that the model was most sensitive to changes in biodegradation rates and hydraulic conductivities, and that small variations in these values produced large changes in plume shape and size. Therefore, the use of bounding (maximum or minimum) biodegradation rates would not permit a reasonable calibration of the groundwater model without excessive variation in other model input parameters. Similarly, biodegradation rates in model Kelly-C produced plumes that differed substantially from the calibrated plume.

Using the maximum calculated biodegradation rate (Table F.3), model Kelly-C results suggest that CB concentrations at the nearest off-Base well (SS003MW001) would rapidly attain the TNRCC action level, possibly within one year. Such rapid losses of contaminants at Site S-1 will only occur if large masses of contaminant are quickly removed, allowing oxygen replenishment. This is expected to occur in the future as the source area is remediated. In contrast, if dissolved oxygen levels (and biodegradation

rates) remain low, possibly due to poor contaminant recovery during source remediation or the cessation of pump-and-treat activities, the possibility exists that the groundwater plume could exist for several decades longer than predicted by the model. If minimum biodegradation rates persist at Site S-1, the model predicts that CB concentrations would migrate much farther than predicted by the calibrated model, and persist for up to a century. However, this scenario is not supported by current CB plume observations, or by the likelihood that a large amount of contaminant mass in the source area will be remediated.

The sensitivity of model Kelly-C to variations in biodegradation rate indicates that the rate used in the calibrated Kelly-C model is reasonable. However, the sensitivity analysis does indicate that if dissolved oxygen levels and biodegradation rates are enhanced as a result of successful source removal, the attainment of TNRCC risk reduction values at off-Base locations may occur much sooner than predicted using either model Kelly-A or Kelly-C. Implementation of a LTM strategy over time (see Section 6) is needed to determine actual plume behavior.

TABLE F.1
CALIBRATED VERSUS OBSERVED
CHLOROBENZENE CONCENTRATIONS (MODEL KELLY-C)
SITE S-1 MNA TS
KELLY AIR FORCE BASE, TEXAS

Calibrated Well Location	Sampling Dates	CB Concentration $(\mu g/L^n)$*	Calibrated CB Concentrations $(\mu g/L)$
Source Area			
SS003MW050	3/7/97	**20,000**	21,960
	6/26/97	1,450	
	8/19/97	14,400	
	3/24/98	11,000	
	6/18/98	14,000	
SS003MW272	4/1/98	**45,000**	45,860
SS003MW121	6/26/97	3,480	
	3/19/98	**14,000**	11,890
SS003MW273	4/1/98	**21,000**	21,030
SS003MW110	9/28/94	5	
	8/15/95	1,300	
	12/14/95	1,740	
	6/27/96	9,535	
	8/14/96	**11,000**	10,770
	12/31/96	8,400	
	3/7/97	7,500	
	6/26/97	10,300	
	8/19/97	10,100	
	3/27/98	5,400	
DOWNGRADIENT			
SS003MW001	7/18/89	13,000	
	1/8/90	11,000	
	10/5/90	9,000	
	12/14/95	1,300	
	12/13/96	2,400	
	3/11/97	1,400	
	6/26/97	3,460	
	11/1/97	**3,500**	6,200
	3/25/98	790	
	6/18/98	830	
SS003MW010	8/3/89	610	
	11/30/89	420	
	10/4/90	280	
	12/14/95	8	
	12/18/96	26	
	3/11/97	28	
	11/1/97	10	
	3/30/98	**45**	275
	6/18/98	5	
SS003MW016	11/29/89	610	
	1/8/90	450	
	10/5/90	600	
	12/14/95	14	
	11/1/97	<1	
	3/26/98	49	
	6/18/98	<1	
	Avg: 12/14/95 to 6/18/98	**16**	14

a/ $\mu g/L$-migrograms per liter.

*Note: Bold value indicates the CB concentration used for model calibration.

TABLE F.2
SUMMARY OF MODELED CHLOROBENZENE CONCENTRATIONS (MODEL KELLY-C)
BIODEGRADATION RATE = 2.7 x 10^{-3} day^{-1}
SITE S-1 MNA TS
KELLY AIR FORCE BASE, TEXAS

Monitoring Well	Calibrated Plume	Predicted CB Concentrations (micrograms per liter)				
		1999	2000	2004	2009	2019
SS003MW050	21960	16522	10014	997	756	594
SS003MW272	45860	48965	10244	663	483	463
SS003MW121	11890	12861	6710	504	389	346
SS003MW273	21030	19943	10383	1291	760	615
SS003MW110	10770	12733	7422	728	451	342
SS003MW001	6200	4350	3600	712	217	165
SS003MW010	275	241	257	212	12	7
SS003MW016	14	14	15	12	3	<1

TABLE F.3
SUMMARY OF MODELED CHLOROBENZENE CONCENTRATIONS (MODEL KELLY-C)
BIODEGRADATION RATE = 1.9 x 10^{-2} day^{-1}
SITE S-1 MNA TS
KELLY AIR FORCE BASE, TEXAS

Monitoring Well	Calibrated Plume	Predicted CB Concentrations (micrograms per liter)				
		1999	2000	2004	2009	2019
SS003MW050	6400	5371	2809	246	264	216
SS003MW272	17920	18447	1884	161	170	142
SS003MW121	4064	4281	1902	148	150	135
SS003MW273	5090	3318	1606	228	202	167
SS003MW110	1925	2835	1274	96	92	69
SS003MW001	132	94	52	6	5	4
SS003MW010	<1	<1	<1	<1	<1	<1
SS003MW016	<1	<1	<1	<1	<1	<1

TABLE F.4
SUMMARY OF MODELED CHLOROBENZENE CONCENTRATIONS (MODEL KELLY-C)
BIODEGRADATION RATE = 7.9 x 10^{-4} day^{-1}
SITE S-1 MNA TS
KELLY AIR FORCE BASE, TEXAS

| Monitoring Well	Calibrated Plume	Predicted CB Concentrations (micrograms per liter)				
		1999	2000	2004	2009	2019
SS003MW050	29922	24131	16435	2068	1070	828
SS003MW272	63601	65733	18863	1479	682	572
SS003MW121	18024	18444	10898	988	523	464
SS003MW273	34509	33641	19562	5044	1178	937
SS003MW110	17418	19887	13374	4660	699	529
SS003MW001	14730	10913	10109	2750	550	410
SS003MW010	5788	5361	5343	4866	605	139
SS003MW016	1873	1803	1863	1674	990	32
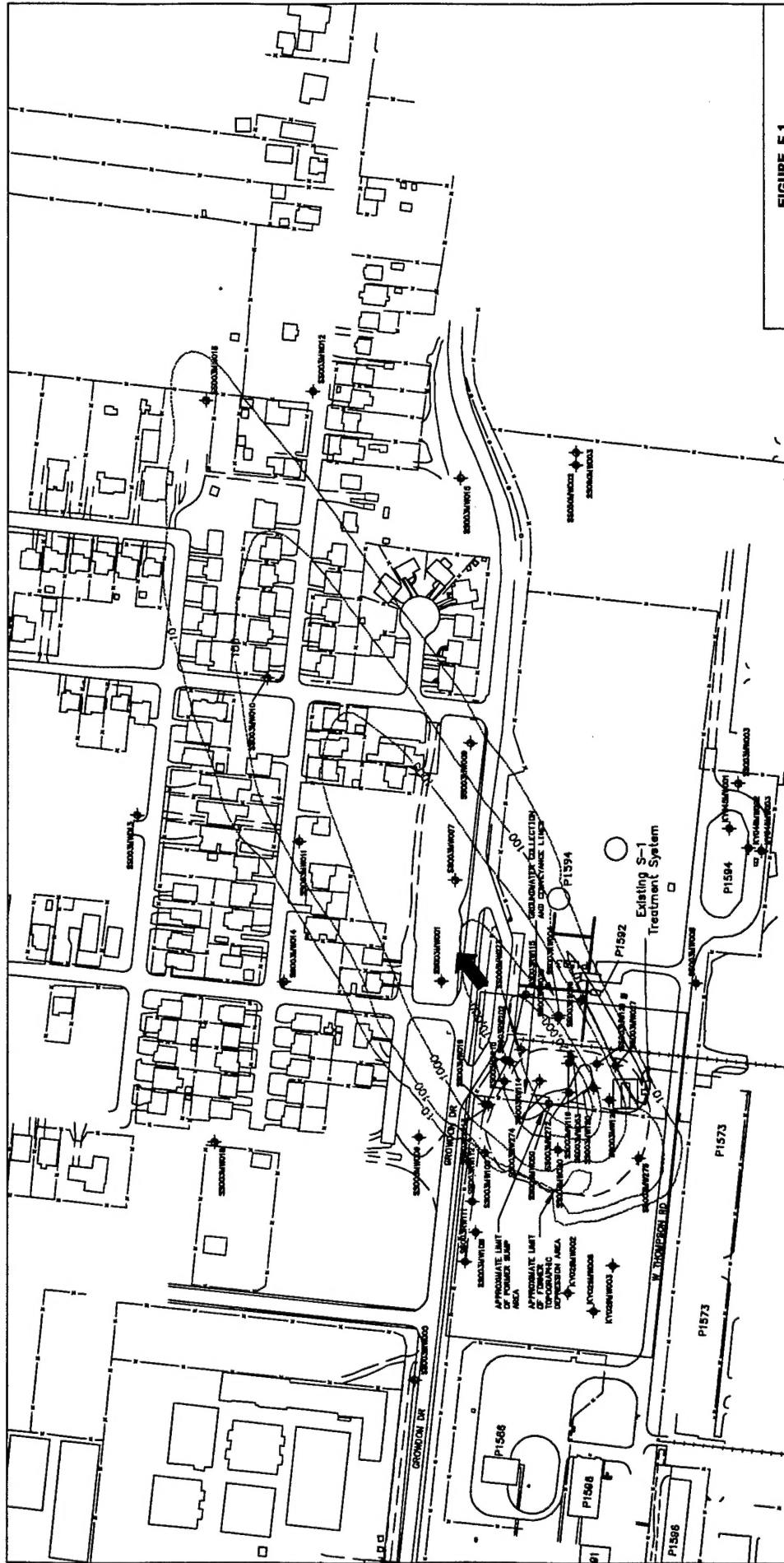
FIGURE F.1

CALIBRATED
CB PLUME
MODEL KELLY-C

Site S-1 MNA TS
Kelly Air Force Base, Texas
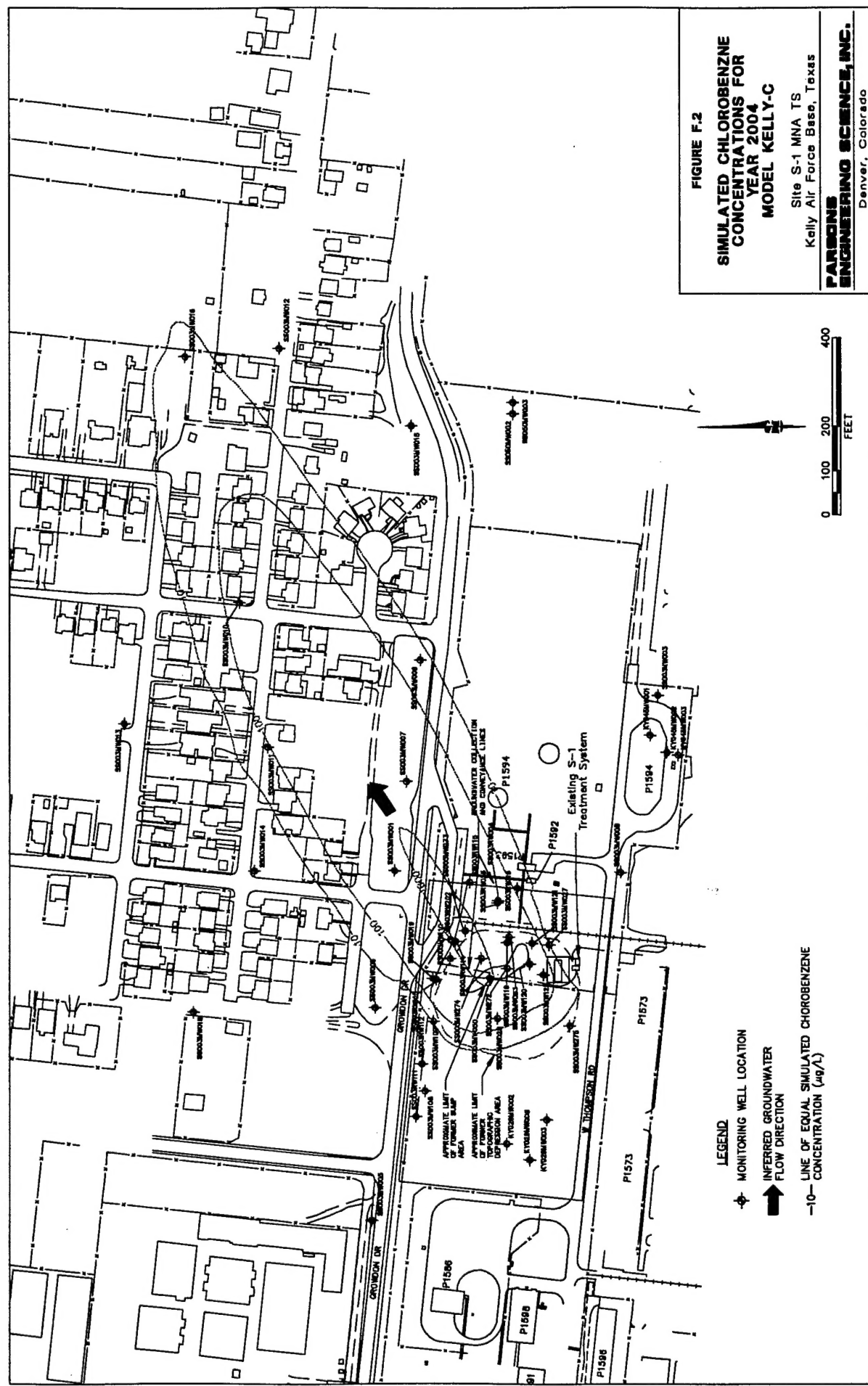
PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado

LEGEND

MONITORING WELL LOCATION

INFERRED GROUNDWATER
FLOW DIRECTION

—0— LINE OF EQUAL SIMULATED CHOROBENZENE
CONCENTRATION (μg/L)

FEET

0   100   200   400

FIGURE F.2

SIMULATED CHLOROBENZNE CONCENTRATIONS FOR YEAR 2004 MODEL KELLY-C

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS ENGINEERING SCIENCE, INC.
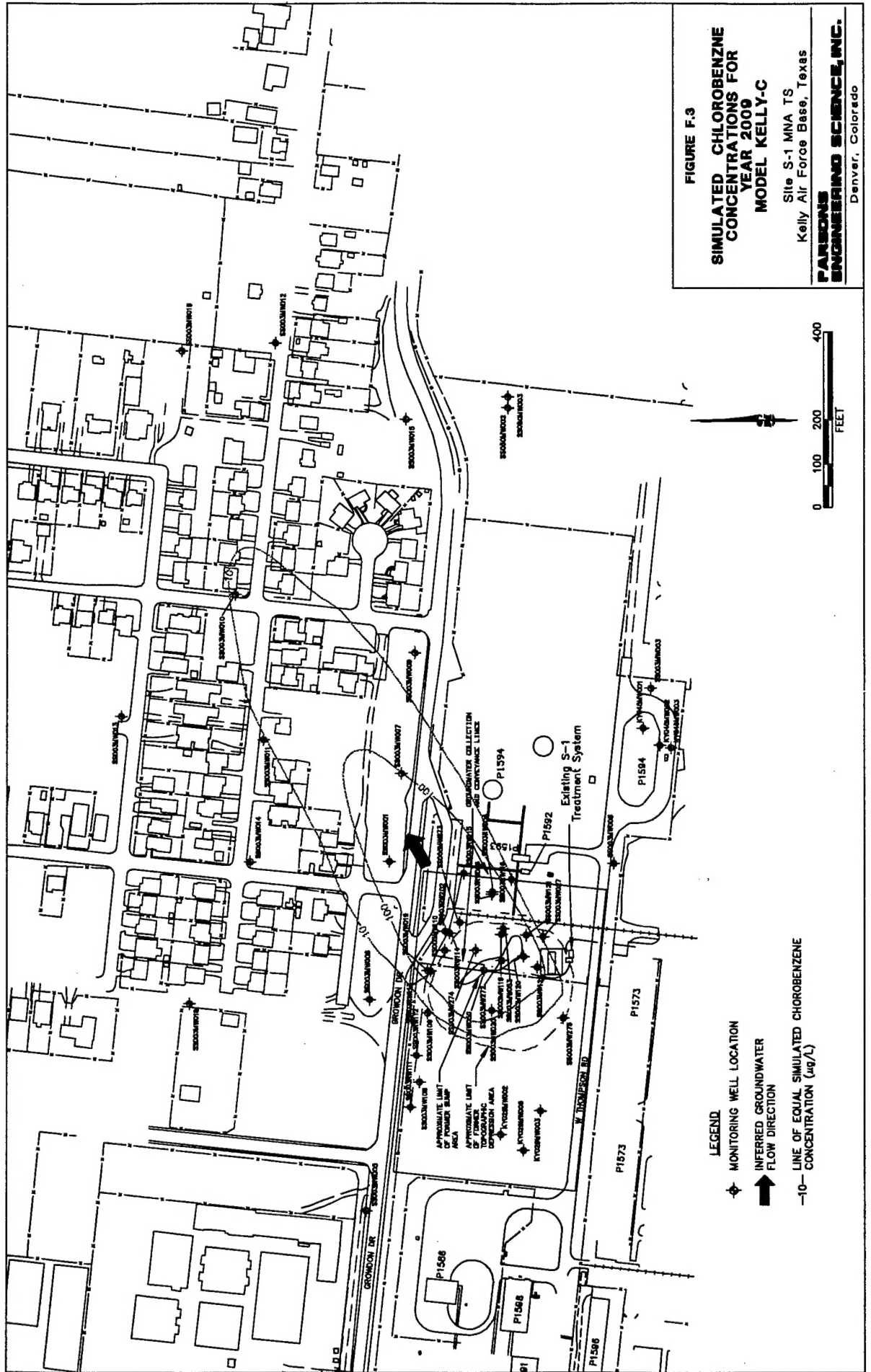Denver, Colorado

LEGEND

✦ MONITORING WELL LOCATION

➤ INFERRED GROUNDWATER FLOW DIRECTION

—10— LINE OF EQUAL SIMULATED CHOROBENZENE CONCENTRATION (μg/L)

0   100   200   400
FEET

FIGURE F.3

SIMULATED CHLOROBENZENE CONCENTRATIONS FOR YEAR 2009 MODEL KELLY-C

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado

LEGEND

⊕ MONITORING WELL LOCATION

▲ INFERRED GROUNDWATER FLOW DIRECTION

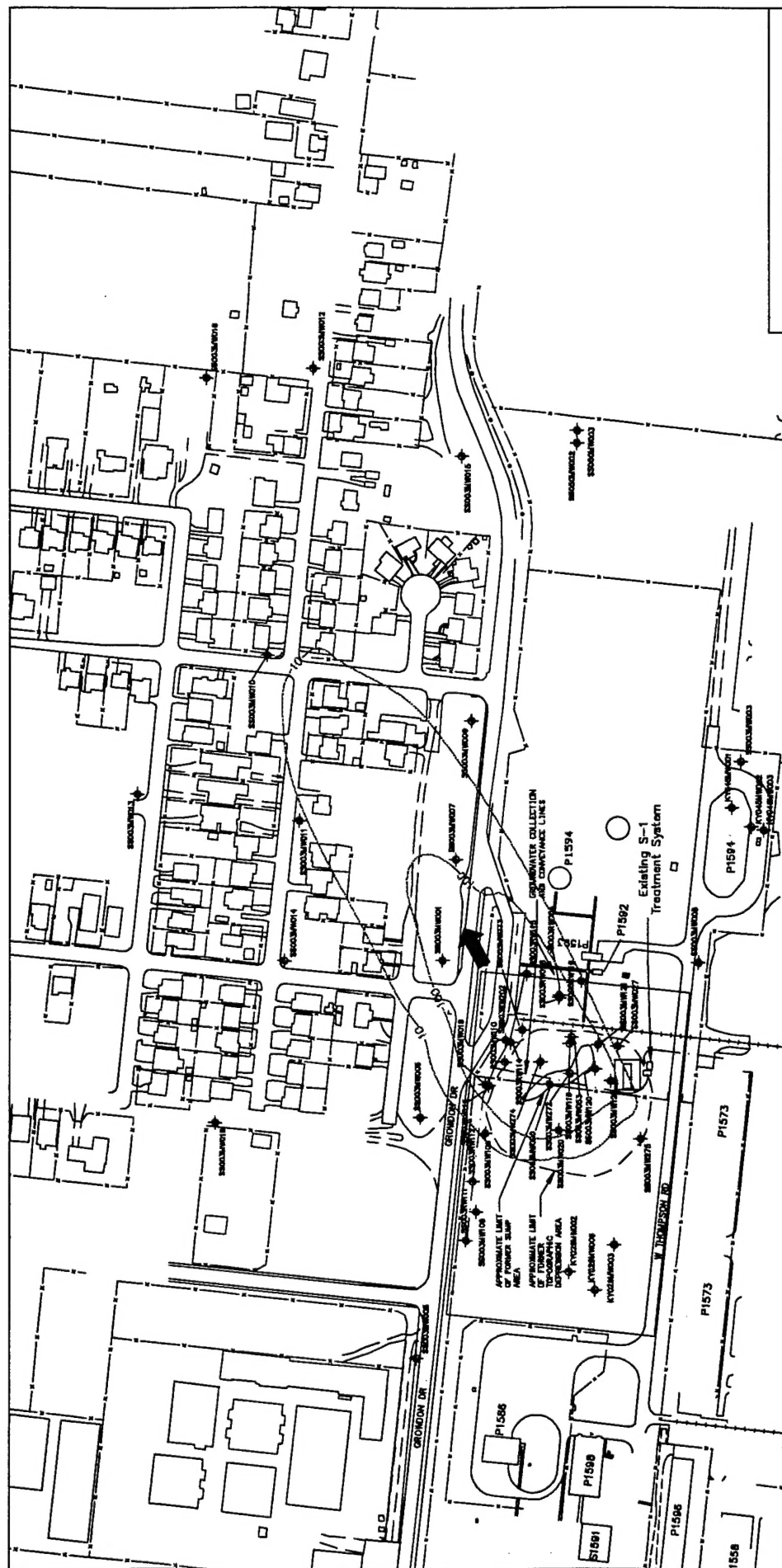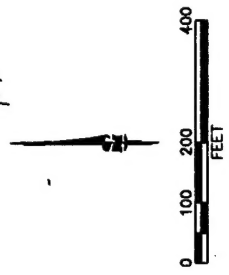—10— LINE OF EQUAL SIMULATED CHLOROBENZENE CONCENTRATION (µg/L)

0 100 200 400
FEET

FIGURE F.4

SIMULATED CHLOROBENZENE
CONCENTRATIONS FOR
YEAR 2019
MODEL KELLY-C

Site S-1 MNA TS
Kelly Air Force Base, Texas

PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado

LEGEND

◆ MONITORING WELL LOCATION

➤ INFERRED GROUNDWATER
   FLOW DIRECTION

—10— LINE OF EQUAL SIMULATED CHOROBENZENE
     CONCENTRATION (µg/L)